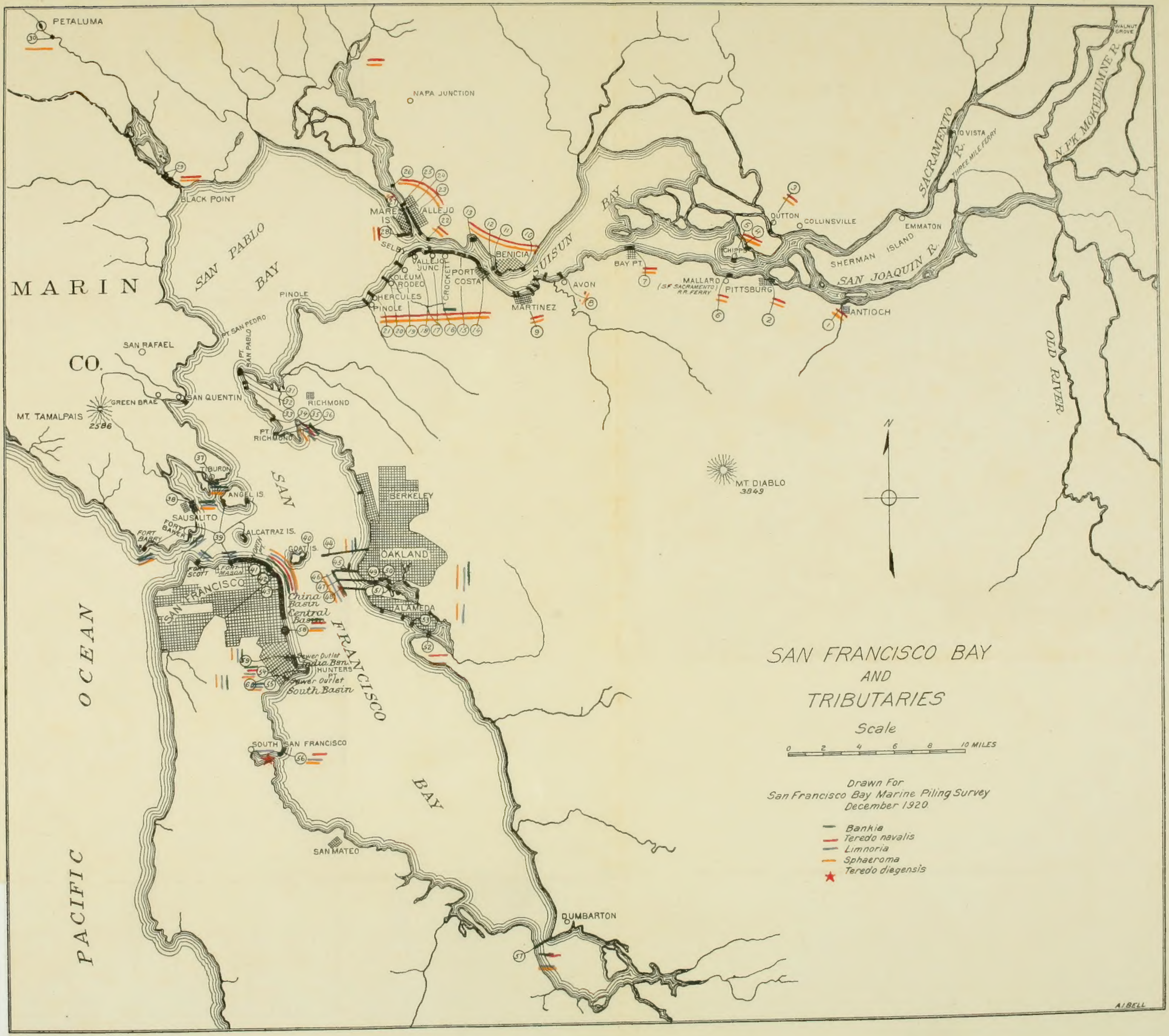
MARINE BORERS AND THEIR RELATION TO MARINE CONSTRUCTION ON THE PACIFIC COAST

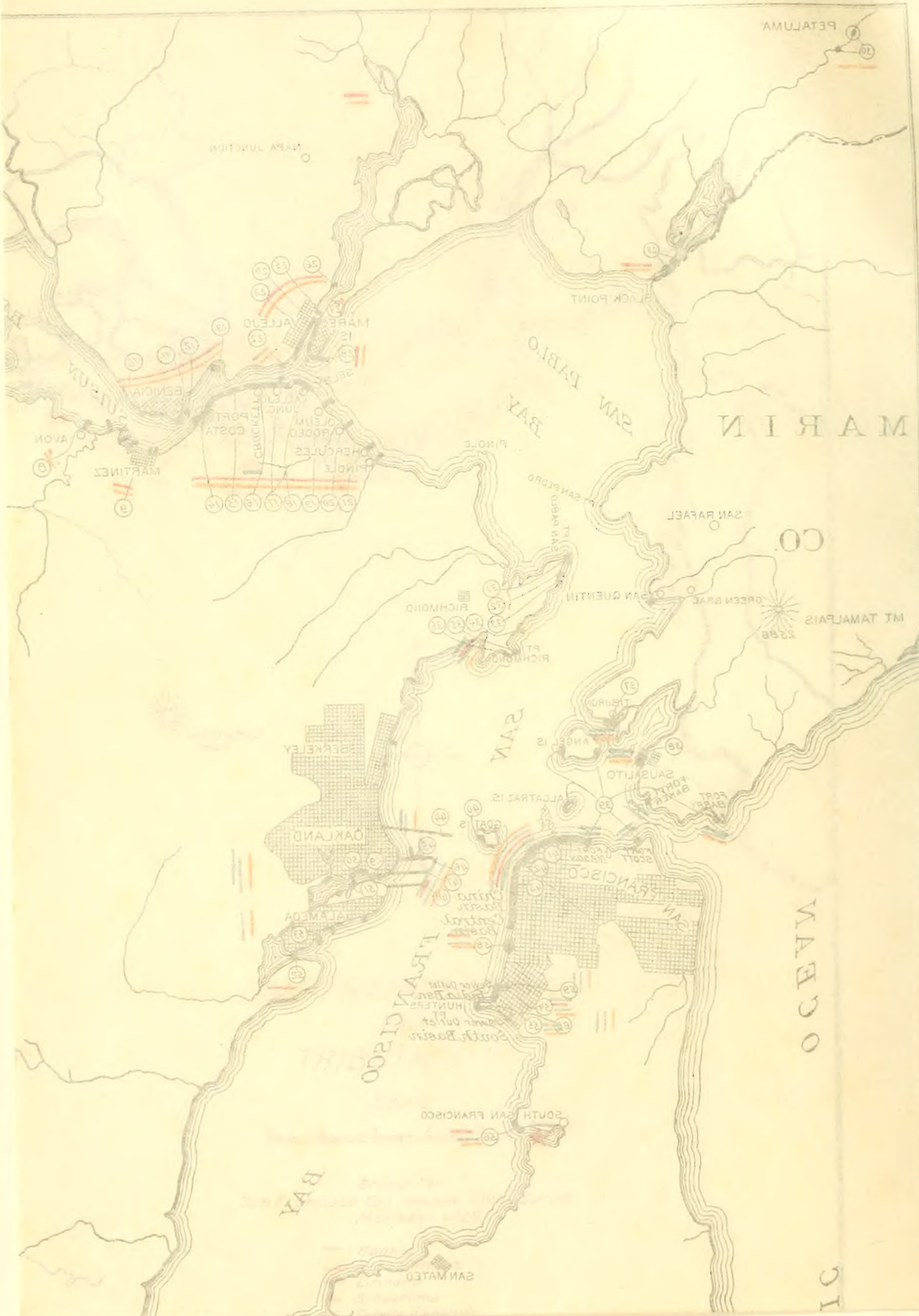
FINAL REPORT

OF THE

SAN FRANCISCO BAY MARINE PILING COMMITTEE

C. L. Hill *and* C. A. Kofoid
Editors-in-Chief


SAN FRANCISCO BAY
AND
TRIBUTARIES
Scale
0 2 4 6 8 10 MILES
Drawn For
San Francisco Bay Marine Piling Survey
December 1920
Bankia
Teredo navalis
Limnoria
Sphaeroma
Teredo diegensis
PETALUMA
NAPA JUNCTION
BLACK POINT
SAN PABLO BAY
MARIN CO.
MARE IS.
VALLEJO
SELBY
VALLEJO JUNC
OLEUM
RODEO
HERCULES
PINOLE
CROCKETT
PORT COSTA
BENICIA
MARTINEZ
SUISUN BAY
AVON
BAY PT.
MALLARD
(S.F. SACRAMENTO R.R. FERRY)
PITTSBURG
CHIPPS
DUTTON
COLLINSVILLE
EMMATON
SHERMAN ISLAND
SAN JOAQUIN R.
ANTIOCH
SACRAMENTO R.
RIO VISTA
THREE MILE FERRY
WALNUT GROVE
N. FK. MOKELUMNE R.
OLD RIVER
PINOLE PT.
PT. SAN PEDRO
PT. SAN PABLO
SAN RAFAEL
SAN QUENTIN
GREEN BRAE
MT. TAMALPAIS
2586
RICHMOND
PT. RICHMOND
TIBURON
ANGEL IS.
SAUSALITO
FORT BAKER
FORT BARRY
ALCATRAZ IS.
GOAT IS.
FORT SCOTT
FORT MASON
SAN FRANCISCO
BERKELEY
OAKLAND
ALAMEDA
China Basin
Central Basin
Sewer Outlet
Islais Basin
HUNTERS PT.
Sewer Outlet
South Basin
SAN FRANCISCO BAY
SOUTH SAN FRANCISCO
SAN MATEO
DUMBARTON
MT. DIABLO
3849
PACIFIC OCEAN
N
A. I. BELL



NUMBERS AND NAMES FOR MAP OF SAN FRANCISCO BAY AND TRIBUTARIES

1. Antioch—A. T. & S. F. R. R. dock; Municipal dock.
2. Pittsburg—Small docks.
3. Dutton—S. F.-Sacramento R. R. drawbridge.
4. Dutton—S. F.-Sacramento R. R. trestle.
5. Chipps—S. F.-Sacramento R. R. ferry slip.
6. Mallard—S. F.-Sacramento R. R. ferry slip.
7. Bay Point—Coos Bay Lumber Co.; Pacific Coast Shipbuilding Co.
8. Avon—Associated Oil Co.
9. Martinez—General Chemical Co.; Electrolytic Zinc Co.; Mountain Copper Co.; American-Oriental Co.; Shell Co. of California; Municipal wharf and ferry.
10. Benicia—U. S. Arsenal pier.
11. Benicia—Kullman-Salz Co.; C. W. Hume & Co.; S. P. Co. river dock; Municipal wharf and ferry.
12. Benicia—Southern Pacific Co. ferry slips.
13. Benicia—U. S. Shipping Board pile boom.
14. Port Costa—Associated Oil.; Southern Pacific Co. ferry slips; McNear warehouses.
15. Port Costa—Granger's dock.
16. Crockett—Fort Bragg dock; Banker's dock; California and Hawaiian Sugar Refining Co. (location of test station C); 6-Minute ferry; Matson Navigation Co.; Port Costa Lumber Co.
17. Vallejo Junction—Southern Pacific Co. ferry to Vallejo.
18. Selby—American Smelting and Refining Co. dock (condemned).
19. Oleum—Union Oil Co.
20. 6-Minute ferry to Vallejo.
21. Hercules—Hercules Powder Co.; Fernandes wharf.
22. South Vallejo—6-Minute ferry to Crockett.
23. South Vallejo—U. S. Navy dyke 9; Sperry Flour Co.; Southern Pacific Co. ferry to Vallejo Junction; ferry to Rodeo.
24. Vallejo—Various small docks and bulkheads; Monticello Steamship Co.; San Francisco, Napa and Calistoga R. R.; Southern Pacific ferry to Vallejo Junction; ferry to Navy Yard.
25. Vallejo—U. S. Navy, causeway.
26. Napa Junction—Associated Oil Co.
27. Mare Island—U. S. Navy structures.
28. Mare Island—U. S. Navy, dyke 12 (location of test station D).
29. Black Point—Northwestern Pacific R. R. bridge; State Highway bridge.
30. Petaluma—Small docks in Petaluma; Northwestern Pacific R. R. bridge.
31. Point San Pablo—Richmond Belt Railway.
32. Point San Pablo—Standard Oil Co.
33. Point San Pablo—California Wine Growers' Association.
34. Point Richmond—Standard Oil Co.
35. Point Richmond—A. T. & S. F. R. R. ferry.
36. Point Richmond—Richmond Municipal wharf.
37. Tiburon—Northwestern Pacific R. R. ferry.
38. Sausalito—Northwestern Pacific R. R. ferry.
39. Angel Island, Fort Baker, Fort Barry, Fort Scott, Alcatraz Island, Presidio, Fort Mason—U. S. Army docks.
40. Goat Island—U. S. Naval Training Station.
41. San Francisco—State Harbor Commission piers (odd numbers) (location of test station B).
42. San Francisco—Ferry slips.
43. San Francisco—State Harbor Commission piers (even numbers).
44. Oakland—Key System pier (formerly S. F.-O. T. Rys.).
45. Oakland—Union Construction Co.; Albers Milling Co.
46. Oakland—Southern Pacific Co. Oakland Mole (location of test station A).
47. Oakland—Western Pacific R. R. ferry slips.
48. Alameda—Southern Pacific Co. ferry slips.
49. Oakland—Moore Shipbuilding Co.
50. Oakland—Structures in Estuary.
51. Alameda—Bethlehem Steel Corporation shipyard.
52. Alameda—Alameda County bridge to Bay Farm Island.
53. Alameda—Alameda Power House pier.
54. Hunters Point—State pile boom.
55. Hunters Point—Drydock.
56. South San Francisco—Shaw-Batcher shipyard.
57. Dumbarton—Southern Pacific Co. Dumbarton Cut-off bridge.
58. Islais Creek—Hammond Lumber Co. pile boom.
59. India Basin—Sewer outlet.
60. South Basin—Bay View sewer outlet.

MARINE BORERS AND THEIR RELATION TO MARINE CONSTRUCTION ON THE PACIFIC COAST

BEING THE

FINAL REPORT

OF THE

SAN FRANCISCO BAY MARINE PILING COMMITTEE

PREPARED UNDER THE DIRECTION OF THE SAN FRANCISCO BAY MARINE PILING COMMITTEE

COOPERATING WITH THE

NATIONAL RESEARCH COUNCIL

AND THE

AMERICAN WOOD-PRESERVERS' ASSOCIATION

C. L. Hill *and* C. A. Kofoid
Editors-in-Chief

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Among organizations which, besides large financial contributions, have given most generously, in facilities for and assistance in the conduct of the Committee work, are the Southern Pacific Company, the Charles R. McCormick Lumber Company, the California and Hawaiian Sugar Refining Corporation, the Board of State Harbor Commissioners, the Associated Oil Company, and the Shell Company of California. While not appearing in the list of financial contributors, the University of California, in laboratory space and facilities, in the unstinted work of scientific specialists, and in the guidance of the Scientific Advisory Committee which it appointed for this Committee, has made a contribution of such magnitude that the results which the Committee presents in this volume would have been impossible without its cooperation. Major cooperation both in scientific assistance and administrative participation was also rendered by the United States Forest Service through its California District at San Francisco, as well as through the Forest Products Laboratory at Madison, Wisconsin. Special courtesies were extended and assistance rendered in conspicuous degree by the U. S. Lighthouse Service; the U. S. Army Engineers, Rivers and Harbors, and Fort Mason; the U. S. Navy, Mare Island Navy Yard, and Eleventh District Headquarters, San Diego; the Los Angeles City Harbor Department, San Pedro; and by numerous private companies throughout the San Francisco Bay region.

The Committee is indebted for unremitting effort in behalf of its work to its officers, past and present, Messrs. F. D. Mattos, A. A. Brown, E. M. Blake, W. C. Ball, J. W. Kelly, and C. L. Hill. Large service, in many cases continuing throughout the project, has been rendered to the Committee either in its field work or in the preparation of this report by many Committee members, among whom should be specially mentioned Dr. C. A. Kofoid, L. D. Jurs, Frank G. White, W. H. Kirkbride, J. S. Burd, and C. E. Cortes, of the Executive Committee, C. E. Grunsky, George M. Hunt, Capt. C. S. Jarvis, R. M. Neily, Jerome Newman, Capt. H. W. Rhodes, H. E. Squire, J. W. Williams, H. J. Wilson, Dr. Robert C. Miller, Dr. W. D. Ramage, H. M. Goodman, C. A. Wilson and R. M. Alpen. Acknowledgments for many specific courtesies or services are made at appropriate points in the text of this report.

THE COMMITTEE.

CONTRIBUTORS TO THE COMMITTEE FUND

American Wood-Preservers' Association.
Associated Oil Co.
Atchison, Topeka & Santa Fe R. R.
Balfour, Guthrie & Co.
Bethlehem Shipbuilding Corp.
Board of State Harbor Commissioners.
California & Hawaiian Sugar Refining Corp.
Colman, J. M. Co.
Coos Bay Lumber Co.
Hammond Lumber Co.
Martinez, City of.
Matson Navigation Co.
McCormick, Chas. R. Lumber Co.
Moore Shipbuilding Co.
Mountain Copper Co.
Northwestern Pacific R. R.
Oakland, City of.
Pacific Creosoting Co.
Portland Cement Association.
San Francisco Bridge Co.
San Francisco-Oakland Terminal Railways. (Now Key System Transit Co.)
San Francisco-Sacramento R. R.
Schaw-Batcher Co.
Shell Company of California.
Southern Pacific Co.
Standard Oil Co.
Union Oil Co.
Western Pacific R. R.

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BEING THE

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HISTORICAL SECTION

CHAPTER 1

ORIGIN AND DEVELOPMENT OF THE SAN FRANCISCO BAY MARINE PILING SURVEY PROJECT

By C. L. Hill

Early in the year 1914, the activity of marine borers was noticed in the dykes of the Mare Island Navy Yard, at the upper extremity of San Pablo Bay, which is the northern arm of San Francisco Bay (see frontispiece map), as well as at two nearby points on the east shore of that bay. One of the latter was a dock between Crockett and Vallejo Junction and the other a dock at Oleum, a mile or so south of Crockett. Sporadic attacks of marine borers were reported to have been observed in that region at isolated times running as far back as 1870, although no certainly authentic records of them could be secured. In any case, however, such attacks were of short duration and did no serious damage.

For many years previous to the attack of 1914 the unusual facilities offered around the shores of San Pablo Bay and the waterfront above that bay, including Carquinez Strait, Suisun Bay, and the lower course of the Sacramento River, had attracted many large industries. The waterfront structures erected by these varied industries were all built on untreated piling, because of the absence of marine borer activity in those waters and the belief that the fresh water discharged into San Pablo Bay from the combined flows of the Sacramento and San Joaquin Rivers would prevent any invasion of that area by salt water, sufficient to carry with it the various forms of marine borers.

The attack of 1914 appeared to be sporadic, like the earlier ones. But in 1917 attacks by the same shipworm, which was identified as a teredo, again appeared at and near Mare Island, and during the following years spread very rapidly and increased in severity. In the latter part of 1919 the attacks had progressed to such an extent that parts of waterfront structures and in some cases whole docks began to fail (fig. 1). In 1920 these failures assumed such proportions and became of such frequent occurrence as to constitute a very critical local situation. On June 16, 1920, this situation was brought to the attention of officials of the American Wood Preservers' Association. As a result, a special committee was appointed on July 22, 1920, to study the marine piling problem in San Francisco Bay, with instructions to report at the Seventeenth Annual Meeting of that Association held at San Francisco in

January, 1921. The committee so appointed began its active work late in July, 1920, and was enlarged from time to time as new local interests became enlisted.

Shortly before June 16, 1920, but practically coincident with the above action, the Forest Products Laboratory of the U. S. Forest Service at Madison, Wis., had proposed a plan for the study of the marine piling problem covering the entire coastal

Fig. 1. Dock failures in Carquinez Strait.

(1) One of the first docks which failed. Oleum, California, Oct. 8th, 1919. Several loaded freight cars were plunged into the bay.
(2) Ferry slip at South Vallejo, failed November 4th, 1920.
(3) Municipal Wharf and house, Benicia, California. Collapsed Oct. 7th, 1920.

(*Union Oil Co. Photo.*)

waters of the continental United States. During preceding years this Laboratory, as well as other agencies, had made various local studies of the activities of marine borers and the methods of their control. One such project, initiated in 1910-1911 by the

Forest Products Laboratory and the California District of the Forest Service, in cooperation with the University of California through Professor Charles A. Kofoid for the biological aspects of the problem, had in view a study covering the harbors of California. Two phases of the project were carried out, involving the experimental

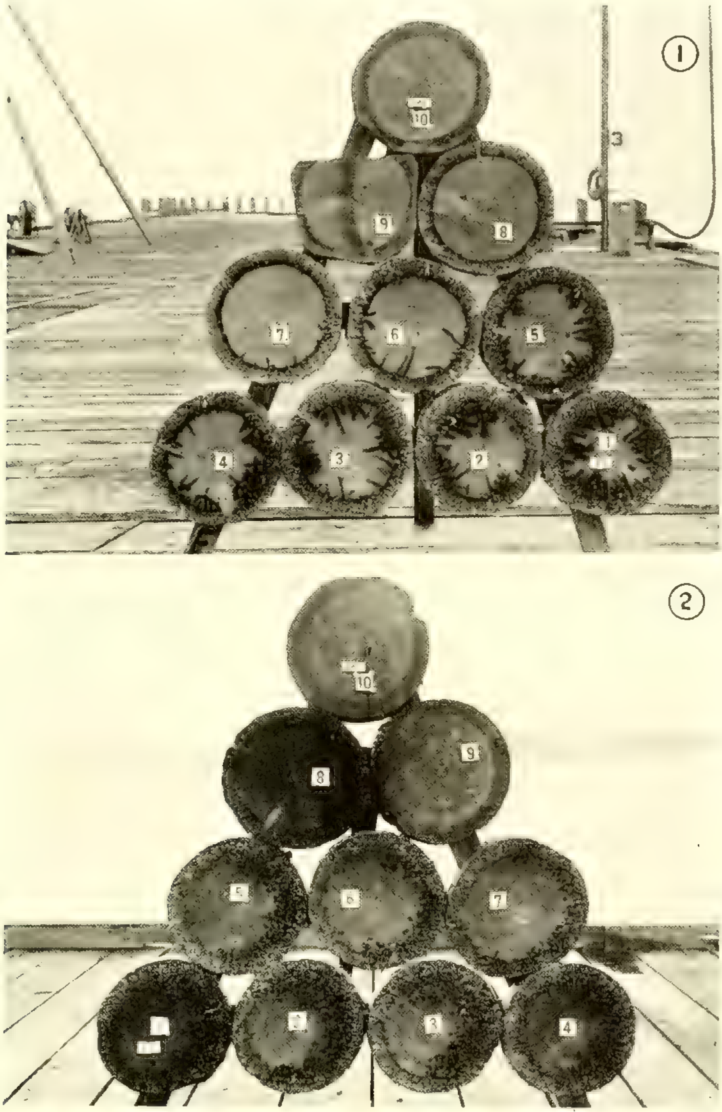

Fig. 2. Destruction of Douglas fir by Teredo.

(1) Fender pile of Douglas fir from wharf of Shell Oil Co., Martinez, California, pulled November 5, 1920, showing penetration of *Teredo navalis* in 1920 (?) at ten equidistant sections. Distance from mud line to high water, 29 feet.

(2) Brace pile from the same wharf in 26 feet of water. Down-stream exposure at left.

(*Shell Oil Co. Photo.*)

testing in the harbors of San Francisco and San Diego of various species of wood, methods of protection, and preservative treatment with different fractions of coal tar creosote. Such studies, however, had been scattered and more or less fragmentary, and the Forest Products Laboratory decided that it was now desirable to bring the

results of all these studies together, and to investigate as thoroughly as possible the entire problem, including the engineering, biological and chemical phases of the subject.

In this situation it was the logical step to unite both proposals and the San Francisco Bay Marine Piling Survey became, therefore, the first unit of the proposed nation-wide program of the Forest Products Laboratory, under joint cooperation with the American Wood-Preservers' Association.

COMMITTEE PERSONNEL

The Committee started with a membership of about 20, which was ultimately increased to more than 50 by the policy of membership representation for those firms or institutions which contributed to the financial support of the Committee, in addition to those selected for specific personal attainments or other reasons deemed of value to the Committee. Some changes in Committee membership were inevitable, due to geographical transfers of members. Losses by death have fortunately been few. In the following complete membership list, the date or dates following the names of members indicate the period of Committee membership or officership.

OFFICERS

F. D. Mattos, Manager Treating Plants, Southern Pacific Company, Pacific Lines, West Oakland, California, General Chairman; Chairman of Sub-Committee on Creosoting, 1920 onward.

E. M. Blake, Production Engineer, Charles R. McCormick Lumber Co., and St. Helens Creosoting Co., San Francisco, Secretary and Fiscal Agent, 1920. Deceased Jan. 12, 1921.

A. A. Brown, Consulting Engineer, California & Hawaiian Sugar Refining Company and Matson Navigation Co., San Francisco, Chairman of Sub-Committee on Wharf Construction, 1920-1921; General Vice-Chairman 1922 onward.

C. L. Hill, In Charge, Office of Forest Products, U. S. Forest Service, San Francisco, Executive Officer, 1920 onward.

MEMBERS OF EXECUTIVE COMMITTEE

With the inauguration of Sub-Committee organization in 1921 the Executive Committee consisted of the officers of the General Committee and the Chairmen of Sub-Committees. The above officers were members ex-officio of all Sub-Committees, including the Executive Committee. In addition there were on the latter:

W. C. Ball, Sales Manager, Charles R. McCormick Lumber Co., San Francisco, Secretary and Treasurer and Chairman of Sub-Committee on Finance, 1920 to 1922.

J. W. Kelly, Sales Manager, Charles R. McCormick Lumber Co., San Francisco, Secretary-Treasurer and Chairman of Sub-Committee on Finance, 1922 onward.

Dr. Charles A. Kofoid, Professor of Zoology, University of California, Berkeley, Calif., Chairman of Sub-Committee on Biological Research, 1920 onward.

J. S. Burd, Professor of Agricultural Chemistry, University of California, Berkeley, California, Chairman of Sub-Committee on Chemical Research, 1920 onward.

C. E. Cortes, Construction Engineer, Shell Company of California, Martinez, California, Chairman of Sub-Committee on Salinities, 1920 onward.

L. D. Jurs, Chief Engineer, Associated Oil Company, San Francisco, Chairman of Sub-Committee on Service Records, 1920 onward.

A. A. M. Russell, Assistant Engineer, Board of State Harbor Commissioners, San Francisco, Chairman of Sub-Committee on Protections, 1922.

Frank G. White, Chief Engineer, Board of State Harbor Commissioners, San Francisco, 1920 onward. Chairman of Sub-Committee on Wharf Construction, 1922 onward.

C. B. Lipman, Professor of Soil Chemistry and Bacteriology, University of California, Berkeley, Calif., Chairman of Scientific Advisory Committee, 1921 onward.

To these in 1922 were added:

H. H. Hall, Chief Engineer, Standard Oil Company, San Francisco.

W. H. Kirkbride, Engineer Maintenance of Way and Structures, Southern Pacific Company, Pacific Lines, San Francisco, member 1920 onward.

OTHER MEMBERS OF THE GENERAL COMMITTEE

Ernest Bateman, Chemist in Forest Products, Forest Products Laboratory, Madison, Wisconsin, 1921 onward.

A. M. Baxter, President, J. H. Baxter & Company, San Francisco, 1920 onward.

J. M. Brady, J. H. Baxter & Company, San Francisco, 1922 onward.

Ralph A. Beebee, Harbor Engineer, Oakland, California, 1922 and 1923.

J. C. Bennett, Assistant Engineer, Associated Oil Company, San Francisco, 1922 onward.

G. W. Boschke, Chief Engineer, Southern Pacific Company, Pacific Lines, San Francisco, 1922 onward.

H. J. Brunnier, Consulting Structural Engineer, San Francisco, 1920 onward.

E. I. Clawiter, Secretary and Engineer, San Francisco Bridge Company, San Francisco, 1922 and 1923.

Captain Leonard M. Cox, Public Works Officer, U. S. Navy Yard, Mare Island, California, 1922 onward.

H. O. Demeritt, Assistant Engineer, San Francisco-Oakland Terminal Railways, Oakland, California, 1921 onward.

Charles Derleth, Jr., Dean, College of Civil Engineering, University of California, Berkeley, California, 1921 onward.

W. W. DeWinton, Engineer, Moore Shipbuilding Company, Oakland, California, 1921 onward.

W. H. Dore, Assistant Professor of Agricultural Chemistry, University of California, Berkeley, California, 1921 onward.

J. M. Evans, Assistant Engineer, Standard Oil Company, San Francisco, 1922 onward.

H. F. Faull, Sales Manager, Hammond Lumber Company, San Francisco, 1921 onward.

Emanuel Fritz, Assistant Professor of Forestry, University of California, Berkeley, California, 1921 onward.

H. M. Goodman, Chief Engineer's Office, Associated Oil Company, San Francisco, 1922 onward.

C. E. Grunsky, Consulting Engineer, San Francisco, 1920.

G. H. Hicks, Acting Chief Engineer, Northwestern Pacific R. R., San Francisco, 1921 onward.

D. R. Hoagland, Associate Professor of Agricultural Chemistry, University of California, Berkeley, California, 1921 onward.

Lieut. Allen Hoar, Corps of Civil Engineers, U. S. Navy, 1920, (transferred in 1921 from Mare Island Navy Yard to Bremerton Navy Yard, Bremerton, Washington).

Howard C. Holmes, Consulting Engineer, San Francisco, 1921; deceased October 30, 1921.

George M. Hunt, in Charge, Section of Wood Preservation, Forest Products Laboratory, Madison, Wisconsin, 1920 onward.

W. M. Jaekle, Assistant Engineer Maintenance of Way and Structures, Southern Pacific Company, Pacific Lines, San Francisco, 1920 onward.

Captain C. S. Jarvis, Corps of Engineers, U. S. Army, Fort Mason, San Francisco, 1920 (until transferred).

Capt. F. B. Jones, Corps of Engineers, U. S. Army, Fort Mason, San Francisco, 1921 onward.

F. D. Kinnie, Assistant Engineer, Atchison, Topeka & Sante Fe Railroad, San Francisco, 1922 onward.

C. A. Kupfer, Consulting Engineer, Berkeley, California, (now transferred to Portland, Ore.), 1921 onward.

Lieut. C. L. Macrae, Corps of Civil Engineers, U. S. Navy, 1920 onward; transferred 1922 from Mare Island Navy Yard to Headquarters, 13th Naval District, San Diego, Calif.

Chas. R. McCormick, President, Chas. R. McCormick Lumber Co., San Francisco, 1920 onward.

Fred H. Muhs, Vice-President, San Francisco Bridge Company, San Francisco, 1920-1921.

Walter Mulford, Professor of Forestry, University of California, Berkeley, California, 1921 onward.

R. M. Neily, Assistant Engineer, Southern Pacific Company, Pacific Lines, San Francisco, 1922 onward.

F. Neitzel, Superintendent of Construction, Bethlehem Shipbuilding Corporation, San Francisco, 1922.

Jerome Newman, Consulting Engineer, San Francisco, 1921 onward.

H. S. Pond, formerly Engineer, Rivers and Harbors, U. S. Engineers' Office; Member of Redmond, Page & Pond, Contracting Engineers, San Francisco, 1921 onward.

C. W. Porter, Associate Professor of Chemistry, University of California, Berkeley, California, 1921 onward.

R. H. Rawson, Consulting Timber Engineer, Portland, Oregon, 1920 onward.

G. W. Rear, Engineer of Bridges, Southern Pacific Company, Pacific Lines, San Francisco, 1921 onward.

Ralph J. Reed, Chief Engineer, Union Oil Company, Los Angeles, California, 1922 onward.

Captain H. W. Rhodes, In Charge, U. S. Lighthouse Service, San Francisco, 1921 onward.

W. T. Richards, Assistant Engineer, San Francisco-Sacramento Railroad, Oakland, California, 1921 onward.

W. L. Shaw, Manager of Grain Department, Balfour, Guthrie & Company, San Francisco, 1922.

F. B. Smith, Consulting Engineer, San Francisco, 1921 onward.

O. K. Smith, Assistant Superintendent, Mountain Copper Company, Martinez, California, 1921 onward.

R. G. Smith, Assistant Manager Fuel Oil & Asphalt Division, Standard Oil Company, San Francisco, 1921 onward.

H. M. Smitten, Bridge Engineer, Western Pacific Railroad, San Francisco, 1922 onward.

H. E. Squire, Assistant Engineer, Board of State Harbor Commissioners, San Francisco, 1922 onward.

J. J. Walsh, Consulting Engineer, San Francisco, 1922 onward.

O. R. West, Division Engineer, A. T. & S. F. R. R., 1920-1921; transferred from San Francisco to Needles, California, 1921.

Frank G. White, Chief Engineer, Board of State Harbor Commissioners, San Francisco, 1920 onward.

J. W. Williams, Chief Engineer, Western Pacific Railroad, San Francisco, 1920 onward.

Chas. R. Wilson, Jr., Chas. R. McCormick Lumber Co., San Francisco, 1921 onward.

*Lieut. H. E. Wilson, C. E. C., Public Works Department, U. S. Navy Yard, Mare Island, California, 1922 onward.

H. J. Wilson, Supt. of Fire Protection, Associated Oil Co., San Francisco, 1922 onward.

†Herman von Schrenk, Consulting Timber Engineer, St. Louis, Missouri, 1921 onward.

COMMITTEE EMPLOYES

Robert C. Miller, Ph.D., Biologist, 1921-1925.
Harold F. Blum, A.B., Biologist, 1922-1923.
Edgar L. Lazier, A.B., Biologist, 1922-1923.
T. R. Hogness, Ph.D., Chemist, 1920-1921.
W. H. Hampton, Ph.D., Chemist, 1921-1922.
W. D. Ramage, Ph.D., Chemist, 1922-1925.
H. M. Goodman, B.S. in C.E., Engineer, 1921-1922.

EMPLOYED BY FOREST PRODUCTS LABORATORY ASSIGNED TO COMMITTEE COOPERATION

T. G. Townsend, Engineer in Forest Products, 1920 only.

*Deceased.
†Consulting member

OBJECTS AND ORGANIZATION OF THE WORK

The objects of the survey were to determine the extent of the damage from marine borers in San Francisco Bay, especially that of epidemic severity which had occurred within the preceding three years in the northern portion of the bay; to determine the present distribution of the several marine borers and as much of their past history in the bay as it was possible to learn; to increase the present knowledge of the dissemination, growth and habits of the borers; to study the factors influencing the rate of attack and amount of damage from them, including the effects of climate and river discharge upon the salinity conditions in the bay; to throw more light upon the effectiveness, both in physical life and economic advantage, of the various methods of protecting wooden piling, and of the substitutes for it, together with the best methods of construction which had been developed; and to collect data on the relative costs of the different methods of protection and construction.

In order to accomplish these objects, the investigation was organized during the first half year, or preceding the first report, along the following lines:

1. HYDROGRAPHIC PHASE

This phase had to do with the effect of climatic conditions and river discharge upon the salinity of the water in the northern arm of San Francisco Bay and its tributaries. This part of the survey was entrusted to Mr. C. E. Grunsky and Captain C. S. Jarvis, whose eminence in that field, as well as their familiarity with the conditions and problems of the Sacramento and San Joaquin Rivers and their watersheds, particularly fitted them for this service.

2. BIOLOGICAL PHASE

This phase had to do with the present distribution of marine borers, their past history, their dissemination, growth and habits, and the factors influencing their rate of attack and the resulting damage. This part of the survey was entrusted to Professor Chas. A. Kofoid, whose preeminent position in this field made his availability to the Committee peculiarly fortunate.

3. ENGINEERING PHASE

This phase had to do with the design, construction, maintenance and repair, with their costs, of marine waterfront structures subject to the attack of marine borers, and covered an investigation of many different methods of protection against such attacks. The sound guidance of this phase of the work was amply assured by the number and eminence of the engineers who not only have been enrolled in the committees but who have devoted themselves actively to the prosecution of its labors. During the most important part of the initial year's survey, the Committee was fortunate in having the personal assistance of Mr. George M. Hunt, Chief of the Section of Wood Preservation of the Government Forest Products Laboratory at Madison, Wisconsin. Following the initial period, the engineering field work was conducted by Mr. H. M. Goodman, Engineer of the Committee, under the direction of the Chairmen of the Sub-Committees on Service Records and Wharf Construction.

DEVELOPMENT OF THE SURVEY

A questionnaire was first sent out to the owners of all important waterfront structures in San Francisco Bay and its tributaries, the returns from which not only furnished valuable information to the Committee but also helped in the planning of the various stages of the field investigations. On account of the peculiar problems

involved in the biological phase of the study, it was seen that certain definitely outlined experimental work would be necessary. The importance of uniformity in that work and the fact that much of it would have to be done by widely scattered cooperators made necessary the careful preparation by the Committee of a manual of instructions covering the methods to be followed in the determination of salinity, the placing of test specimens, the preparation and preservation of biological and other specimen material and in the collection and submission of reports and photographs. The form of the questionnaire will be found in Appendix A, and the instructions in Appendix B.

In the work of the survey engineers, besides that of a reconnaissance and survey character, arrangements were made wherever possible for the pulling of piles, and every opportunity possible was taken to witness such pulling where alterations or repairs were in progress. Meanwhile an attempt was made to gather all the information available from the files of cooperating companies and other agencies, both public and private.

The work of the year 1920 was reported to the American Wood-Preservers' Association at its Seventeenth Annual Meeting in San Francisco on January 26, 1921. It clearly demonstrated how large was the field upon which the investigation had entered, and how urgently necessary was not only the continuance of the survey but the extension of the work in the field of research, in order that its largest possible results might be realized. This led to a continuance of the authorization by the Association.

The Committee for the following year, on assuming its duties, concluded that adequate results could not be secured by an investigation continuing for less than three years farther. It also decided that, in addition to such engineering assistance as should prove necessary, the fundamental nature of the biological and chemical problems warranted the employment of both a biologist and a chemist for full time on the Committee work. On this basis the Committee solicited financial support in the amount of $30,000. That such a volume of work has been carried on through so long a period, and really significant results accomplished, on resources so meagre compared to the expenditures of most similar enterprises, has been due to the fact that the Committee has had no overhead expense, quarters and all administrative and supervisory services having been contributed gratis and the entire expenditures going into productive effort.

Upon the organization of the 1921 Committee it was, for the better conduct of the several phases of the work, divided into sub-committees as follows:

Executive
Finance
Service Records
Wharf Construction
Protections
Chemical
Specifications
Biological
Salinities

This subdivision of work resulted in more effective utilization of the interest and energy of the large membership composing the main Committee than could have been accomplished otherwise. The Committee employed, year-long, a biologist and a chemist. During the latter part of the year also a competent engineer was employed on the work of the Service Records Sub-Committee.

COMMITTEE EQUIPMENT

Through the courtesy of the Southern Pacific Company, the Committee was able to establish a biological field laboratory and experiment station on that company's freight pier adjacent to the Oakland Mole. Here, with running water both fresh and salt, marine borers were maintained in continuous health and activity, as well as subjected to varying salinities down to perfectly fresh water. This work permitted a most valuable control check upon the field work in respect to the critical factors operative in the survival and extension of teredo. Here also were tested the toxicity upon marine borers of various creosote constituents and other chemicals. Reached by ladder below the field laboratory was a working platform at the approximate level of high tide, from which experiments under actual tide conditions were conducted.

Fig. 3. Test station A at Oakland Mole, showing the high tide level platform underneath the wharf, with several test gates pulled up for inspection.

This platform and the surrounding piling was also used by the Sub-Committee on Protections for the exposure to borer attack of the various piling protections which it tested.

Through the similar courtesy of the California & Hawaiian Sugar Refining Company, the Committee was later supplied with a second biological field laboratory at Crockett, Calif., just at the critical tension point of teredo's survival in Carquinez Strait during the preceding season (as discussed in the biological section of this report). At this laboratory during several months of 1922, a second biologist in the employ of the Committee carried on special investigations under Professor Kofoid's direction with reference to the factors determining this survival. Here also the Committee installed a recording thermometer for the study of the temperature factor.

In addition to the field laboratories, through the cordial cooperation of the Uni-

versity of California, both the biologist and the chemist of the Committee had the privilege, for Committee work, of the extensive facilities of the University laboratories in their respective sciences.

Four test stations were maintained by the Committee, where specimens of wood treated with different oils or oil fractions were under regular observation, in exposure to borer attack. These stations were at State Harbor Commission Pier 7, San Francisco, the Oakland Mole, the Mare Island Navy Yard, and the California & Hawaiian Sugar Refining Company piers, Crockett. A supplemental station was later added at Fisherman's Wharf, on the San Francisco water front, nearer the Golden Gate. (See frontispiece.)

Eight salinity stations were maintained, at Avon, Bulls Head Point, Martinez, Port Costa, Crockett, Black Point, Greenbrae and Tiburon, from which samples of water, in some cases at both high and low tide, were taken and were analyzed for salinity.

NATIONAL RESEARCH COUNCIL COOPERATION

The San Francisco Bay Marine Piling Committee initiated the movement which resulted in the organization of a special Committee on Marine Piling Investigation by the National Research Council, which was intended to act as the guiding and correlation center for widely distributed investigative activities in this direction, to be undertaken by cooperating agencies at many marine centers of the United States, as well as to form a medium of contact between such activities in the United States and other countries. In furtherance of that object this Committee enlisted for its specifically scientific activities the service of an Advisory Committee composed of men of high scientific rank and attainments, appointed by the President of the University of California from the faculty of that institution, in order to provide for this work the authoritative scientific guidance required as a condition of its sponsorship by the National Research Council. This Committee was composed of the following members:

C. B. Lipman, Professor of Soil Chemistry and Bacteriology, Chairman.

C. W. Porter, Associate Professor of Chemistry.

C. Derleth, Jr., Dean, College of Civil Engineering.

J. S. Burd, Professor of Agricultural Chemistry.

C. A. Kofoid, Professor of Biology.

Walter Mulford, Professor of Forestry and head of the Division of Forestry.

D. R. Hoagland, Associate Professor of Agricultural Chemistry, Secretary.

Upon the organization of the Committee on Marine Piling Investigations of the National Research Council, the San Francisco Committee became affiliated with it and thus, in addition to carrying on its own specific work, it functioned as the California coast collaborator of the National Research Council in this work. This Committee made regular biological examination, for the Council, of test samples of wood exposed in Los Angeles and San Diego harbors as well as of those from eleven Pacific Ocean stations outside the United States proper. A tentative marine borer reconnaissance was also made of the harbors of Los Angeles and San Diego, with some remarkable results.

SUMMARY OF WORK ACCOMPLISHED

Subsequently the Committee has completed a biological study of the marine borers represented in this Bay, which has materially contributed toward bridging the gap previously existing in knowledge of the shipworms between the larval and adult stages, and is believed to be the most complete study of these organisms and of their physical environment as here surrounding them, thus far made. The Committee has compiled service records covering not less than 90 per cent of the approximately 250,000 piles in San Francisco Bay and tributary waters and whose completeness has added much to the assurance with which the life of various piles or piling protections can be estimated. Specifications for creosote and creosoting practice have been presented by the Committee, whose observance it believes will contribute to the production of the most satisfactory treated material for use in marine structures. Through the Sub-Committee on Chemical Research a number of problems have been solved, or their solution materially contributed to, such for example as that respecting the supposed selective filtering action of wood upon creosote injected into it, and the character and probable significance of the progressive decrease in lighter fractions and increase in those of higher boiling point which takes place in the composition of injected creosote during subsequent exposure. The work of this Sub-Committee has also demonstrated the effectiveness, or otherwise, of certain chemical methods of piling protection employing means other than the ones customary in the injection of the preservatives into the wood or their application to its surface. Such, for example, is the so-called electrolytic chlorine process. Through mutual cooperation of the Sub-Committees on Protections, Biology and Chemical Research the extensive exposure tests of the Committee have yielded a material amount of knowledge respecting the comparative value of a large number of proprietary preservatives and processes of piling protection, in respect to which the user of piling products has hitherto had available little or no authentic information. The Committee has also been able to make valuable suggestions for improved construction practice in the erection and maintenance of creosoted wharves and other marine structures, which are being increasingly observed in the San Francisco Bay region, due largely to the Committee's educational efforts. This observance has already reduced greatly the needless damage inflicted upon such structures in that area and bids fair to increase the life of those structures measurably towards the maximum of nearly double the past average, whose possible attainment has been demonstrated by such installations as the now famous Southern Pacific "Long Wharf." In respect to concrete construction, which has a definite and probably an increasing place in marine structures, standards have been worked out by the Committee which are believed to meet the specific and exacting requirements of this field—which seems elsewhere to have received inadequate attention, being dismissed in the monumental "Joint Committee Report" on reinforced concrete, for example, with a single page of discussion.

CHAPTER II

HISTORICAL DEVELOPMENT OF MARINE STRUCTURES IN SAN FRANCISCO BAY

By R. M. Neily

San Francisco Bay, in common with most ocean harbors, has been subject to marine borer activity at least as long as records have been kept in this respect, although tradition says that the shipworm was not known there in Spanish days and did not become a menace until after the large shipping increase in the port which followed the gold rush of 1849.

THE PIONEER PERIOD, UP TO 1869

In 1847, a year before the discovery of gold in California and three years before the State's admission to the Union, the municipality of San Francisco consisted of a settlement of some eight hundred persons, situated near what was known at the time as Yerba Buena Cove. This particular site had been selected many years before for the settlement, for the reason that the mainland elsewhere was very hilly, the shores rising abruptly from the water's edge, and the cove offered a protected ship harbor and possibility of future development. Few ships entered the port, no wharves existed and landing places were of a small and temporary nature.

The possibility of filling the tideland of the cove had been suggested as a means of securing an additional area near sea level, and the sale of property so created was seen as a means of providing funds for the municipal treasury. To this end, the Governor was prevailed upon to cede to the municipality the government tideland rights. A paper survey was immediately made, streets were laid out and an ultimate shore line was established which would close out the cove. That same year the "water lots" were placed on sale and the public came into possession of what was soon to become the waterfront wharf area.

With the discovery of gold the port suddenly became the scene of great activity. By 1849 the "migration" to California was well under way. The transcontinental railroad was still a dream of the future; the gold fields lay westward of the great barrier of the mountains and the most available means of general transportation was by ship. These came from every port in the world. With the sudden demand for wharves, the public, already firmly entrenched on the waterfront, hurriedly built on the "water lots," while companies were organized to build wharves on the "water streets," which were leased from the city. The structures on the former were of haphazard construction, while the latter were prepared with greater care and became the principal dock facilities. In this manner a great wharf area was created, upon which sprang up blocks of buildings where most of the city business was transacted. The first large wharf was that variously known as "Commercial Street," "Long" or "Central" wharf, started in 1849. Within a year, twelve large wharves had been constructed, at an estimated cost of $1,500,000, in addition to the innumerable small structures on the "water lots."

The wooden ships arriving in port were promptly deserted by their crews, who

Fig. 4. San Francisco in 1847, showing Yerba Buena cove (see map, p. 54). The ship marked "A" is close to the present Ferry Building site.

rushed away to the gold fields. These ships accumulated to such an extent that a chronicle of the time records that in 1849 "there were between three and four hundred square rigged vessels lying in the Bay, unable to leave on account of want of hands." A majority of these, and of those to follow in the next few years, never did leave port. Some of the abandoned hulks were purchased and permanently located to serve as wharves and buildings for general purposes. Three of them supplied the new city with standard municipal facilities: the "Euphemia" became a prison, the "Panama" a church, and the "Apollo" a saloon. In a short time the ships numbered "eight to nine hundred—like an immense forest stripped of its foliage."

With the great mass of unprotected timber in the harbor, all conditions were present to promote the propagation and spread of borer infestation. That marine borers were very active at the time is shown by the following quotation from an observer's record of the period: "When I landed again in San Francisco in 1857, I was astonished at the second great change which time and circumstances had wrought . . . Some of the wharves had broken down; others were in a fair way to share the same fate, being veritable man-traps . . . Many of the houses erected on the wharves

Fig. 5. Yerba Buena Cove in 1849.

were unoccupied and tottering on their insecure foundations of piles half demolished by the timber-worm." Thus many of the structures built subsequent to 1849 had become abandoned menaces by 1857; it is recorded that those which continued serviceable were only maintained by continuous renewal of piling.

While the borers present at the time have been variously referred to as "timber-worms," "shipworms" and "teredo," it is likely that *Bankia* was the first form present. This borer is of the family Teredinidae along with the teredo, and although much larger, has the same general appearance and method of attack as the true *Teredo*, which has led to confusion with the latter. There is no definite biological evidence, however, that the *Teredo* was present until about 1913. (See p. 206.) If *Limnoria* had existed at the time it is likely that some of the many writers of that period would have observed and recorded the easily visible manner of its attack on piling, whereby the surface wood is eaten away near low tide level, reducing the pile diameter until it is cut through. Absence of comment by early writers on "teredo" attack, until the wharves began to collapse, is easily explained by the fact that the borers of this family work inside the pile, without visibly affecting the outer surface. The Board of State Harbor Commissioners reported in 1869: "The piles in this harbor are at-

tacked by the shipworm known as the *teredo navalis*"—again with no mention made of *Limnoria*.

Evidence that this borer was observed shortly after 1869 is given by the statement of Mr. T. J. Arnold, Engineer of the Board, in 1873: "The *limnoria terebrans* has only recently made its appearance in our waters." It therefore appears that the three principal borers now present in the Bay became noticeably destructive at the following approximate dates: *Bankia*, 1850; *Limnoria*, 1870; and *Teredo*, 1913. That these were the dates of their arrival in the harbor cannot be established as more than conjecture. Some of the species appear to be indigenous.

Simultaneously with the beginning of wharf construction in 1849, work was started on grading off the sandy hills of the mainland, the excavated material being dumped into the Bay along the shore. In 1851 the State Legislature passed an act defining the city bulkhead line as that formed by certain proposed streets which approximated the desired limit. This caused a saw-toothed alignment in sections

Fig. 6. San Francisco Bay about 1853; Goat Island in background.

where it was necessary to follow around the rectangular street intersections to form a general curve. The act also prescribed that wharves could only be built beyond the waterfront line on extensions of the city streets and for a distance not to exceed two hundred yards. This was the first definite ruling on harbor development to which early structures were required to conform. The ruling was faulty, however, since the streets were laid out only to the waterfront line; hence a wharf extension of any one of them could go in any direction beyond it. This resulted in many interpretations within the law, and many irregular wharves. The filling of the cove area progressed so rapidly that by 1855 the wharves of 1850 were completely surrounded, and other such structures were finding it difficult to keep in advance of the fill far enough to provide adequate depth of water. This presented a new problem because of the lack

of a retaining wall to hold back the fill. The huge quantities of material dumped into the Bay were constantly being washed out by wave action, shoaling the wharves and causing disastrous settlement in those portions first placed. The latter effect was largely due to the fact that whole blocks of buildings had been hurriedly constructed on the new fill without adequate pile foundations.

This situation brought a general realization that such a condition could not continue, and that a seawall must ultimately be built along the waterfront line. The project was actively discussed in the early 50's, but while it was generally acknowledged as necessary, no action was taken for many years because of the great expense involved. It was a foregone conclusion that the wall would eventually be built, cutting off all access by ship to wharves constructed within its line. It soon became apparent, also, that the irregular wharves extending beyond the bulkhead line must ultimately be rearranged according to some definite plan. Thus it was demonstrated that the structures could not be built for permanency, even had materials and necessary funds been available. The condition is mentioned because it is typical of harbors in process

Fig. 7. An early wharf. Telegraph Hill in background. About 1860.

of development, where no final plan has been determined, and where wharves are likely to have a comparatively short economic life. This phase is discussed in detail under the subject of economic life of structures (p. 60).

Meanwhile waterfront development of territories elsewhere around the Bay began in a limited way. Some small wharves were built at Oakland and a ferry service was inaugurated to San Francisco. No deep water wharves were constructed there until 1863.

In San Francisco the "Golden Era" of the first several years was followed by a period of financial depression, starting in 1854, particularly in those branches of industry which had been overdeveloped in the first flush of prosperity; and one of the greatest problems presenting itself was the maintenance of the great number of wharves which had started to collapse because of decay and borer attack. From this time on, records relate the difficulties experienced with these structures, requiring renewal which amounted to complete replacement every four or five years. This condition,

coming at the time of the financial depression, resulted in the abandonment of many wharves, already referred to. Due to this and other influences the general harbor conditions were soon in a chaotic state.

To remedy this situation and secure other benefits, the Board of State Harbor Commissioners was created in 1863 to control the San Francisco waterfront, and this body has continued in control to the present time. When they took up their duties about twenty-five large wharves existed, built for the most part on city streets. It is recorded that on the day before their first meeting the Steuart Street wharf collapsed, dropping 150,000 feet of lumber into the Bay, and that the Vallejo and Jackson Street wharves failed shortly afterward. Rehabilitation of the wharves to place them in operating condition was immediately undertaken as far as limited resources would permit, $67,000 being spent in the first year and $80,000 in the next.

In 1863 the San Francisco & Oakland Railroad Company completed a wharf at Oakland for its rail and ferry terminals "twelve hundred yards long, so that access was given to that town at regular hours, instead of being dependent on the tides as before." This was the start of Oakland Long Wharf, which was later to attract considerable attention because of the long life secured from creosoted piling used in its later construction.

The seawall for San Francisco was now considered urgently necessary, particularly because it would permit a permanent fill where piling was being maintained at great cost. In 1865 the Harbor Board took definite steps to accomplish the project; plans were formulated, and two years later the work began. The starting of the wall gave promise of a permanent waterfront development, but at the same time brought attention to the absolute inadequacy of unprotected timber piling for whatever new piers were projected.

THE SECOND PERIOD: THE RAILROADS; PIONEER EXPERIMENTS IN PILE PROTECTION

In 1869 the Board reported as follows: ". . . the Commissioners have deemed it of great importance to make some experiments with well-known processes for the preservation of timber used in wharf structures. The piles in this harbor are attacked by the shipworm, known as the *Teredo navalis*, and in from three to five years are so much injured as to become entirely worthless. Although this has long been known it is only within the last year that any establishment for the protection of timber against worms and decay has been put in operation on the Pacific Coast. Works during that time have been erected by two companies operating separate processes—the Pacific Wood Preserving Company, using the 'Robbins' patent, and the North American Wood Preserving Company using the 'Samuels' patent." The "Robbins" process consisted of treating piling with condensed vapors of creosote—the injected preservative amounting to about one pound per cubic foot. The nature of the "Samuels" process is not known.

At about this same time it was noted that piles driven with bark on resisted borer attack better than those without bark; and this, with the "Robbins" process, became general practice for many years.

At this critical point in the development of the San Francisco harbor, with revenue decreased because of business depression, income reduced because of unserviceable structures and resources drained by constant heavy renewals, a competitive agency entered the field formerly held exclusively by the shipping interests. In 1869 the Central Pacific-Union Pacific final link in the transcontinental railroad was completed.

The effect of this event on shipping activity can be judged from the fact that the port tonnage dropped from 426,000 in 1867 to 176,000 in 1869. As a result, harbor developments were held up, including construction of the seawall.

While the completion of the railroad seriously curtailed San Francisco port activity, it created a stimulus to industry on the east side of the Bay, which formed the actual or physical terminus of the road. This resulted in the construction of new wharves. In the years 1869 to 1871 the Oakland Pier terminal of the Central Pacific Railroad, already referred to, was extended from a length of about 6,900 feet to over 11,000 feet, and was thenceforth known as "Long Wharf." Some of the piles used were treated with the Robbins process, and a large portion of the balance were driven with bark on. In 1870 wharves were built in the northern tributaries of the Bay, especially in the Carquinez Strait, at Vallejo, Benicia and Port Costa. During this

Fig. 8. Shipping in San Francisco Harbor about 1870, showing early ferries. Note that the piers in the distance make acute angles with those in the foreground.

same year cast iron piles and metal sheathed timber piles were introduced in Government wharves; some of these having been maintained in service to the present time.

In 1873 Chief Engineer S. S. Montague, of the Central Pacific Company, in referring to Oakland Long Wharf, recorded the following: ". . . although it cannot be regarded as permanent, its life will greatly exceed that of the San Francisco wharves, where the ravages of the teredo have been so destructive . . .

"The immunity of the wharves on the eastern side of the Bay from the attacks of the teredo is undoubtedly due to the fresh water from the Strait of Carquinez, which at certain states of the tide, flows along the shore.

"The experiment of using piles treated by the 'Robbins process,' as a preventative

both against decay and the work of the teredo, has been made at Oakland Wharf, and also in some of the new work at Second Street and in the Mission Bay. The piles so treated have thus far withstood the attacks of the teredo . . ."

Irrespective of the correctness of his conclusions as to the reasons for the difference of borer attack at San Francisco and Oakland, the statement is of interest and the difference of attack which he observed has continued to the present time. If fresh water currents were affecting the salinity on the Oakland side, the borer action would have been reduced, had the species there active been *Bankia* or *Limnoria*, but not if *Teredo:* the first two require relatively high salinity whereas the *Teredo* thrives in brackish water. His statement on the Robbins process is typical of the great hopes so commonly held out for the success of new preservatives or methods, and which were so commonly destined to disappointment.

Meanwhile, cessation of work on the San Francisco seawall had proved fortunate, for it was observed that the original saw-toothed waterfront line was producing eddying currents seriously affecting the mud line, sediment being deposited in the slips, causing constant shoaling and requiring excessive dredging. The Harbor Board engineer called attention to this situation, and showed that the only solution would be to abandon the irregular line and create a new line following the tidal currents in a

Fig. 9. Oakland Long Wharf in 1873.

smooth curve. Several years later, in 1878, this new line was officially adopted for the waterfront and the location of the seawall. A new pier arrangement was prepared, and that same year work was started on the first section of the new wall.

Thus after thirty years of fluctuating circumstances, during which millions had been spent on facilities all of which would cease to serve within a few years, the basis of a permanent plan of harbor development was established. The wharves of independent owners which would be cut off by the new seawall had cost several million dollars in the fifteen years since 1863, the Harbor Board had spent $1,446,000 for general wharf repair and construction; the abandoned seawall had cost $691,000; and dredging had cost $510,000. While considering these expenditures, it must be borne in mind that the harbor facilities had always yielded an ample profit. The independent owners had realized huge profits, and the Board a profit of $455,000 in the fifteen years mentioned. The figures are cited to show the proportions reached by the costs of "temporary" facilities during development of the harbor—costs of pile structures, of a seawall to eliminate pile structures, of accompanying dredging—and of profit realized regardless of the exigencies of changing conditions.

Matters continued in this general condition for the next ten years. New piers

were built and many new preservatives for timber were tried with varying success. In this period the Robbins process was found to be comparatively ineffective because the amount of creosote injected was insufficient and soon leached out, leaving the timber unprotected.

THE THIRD PERIOD: SOUND CREOSOTE AND UNSOUND CONCRETE

During the years 1888 to 1890 untreated timber and that treated by the plausible but unproved preservatives or processes of every new inventor began slowly to be mixed to a larger and larger extent with that treated with creosote by the Bethel pressure-cylinder process, which had consistently proved its value ever since its introduction in England in 1838. Since the light treatment of the Robbins process was found effective until it leached out, the obvious conclusion was that the amount injected must be increased. Mr. John Bethell, who had invented and patented the creosoting process by pressure impregnation, had stated that piling should be treated with ten pounds of creosote per cubic foot; but he was simply one of innumerable inventors of the time, his opinion was not generally accepted, and practically fifty years thus elapsed during which the process was under trial, before his opinion was confirmed. During this time gradually accumulating experience indicated that failures with creosote treatment are failures of its application to the timber rather than of the creosote itself and that his invention gave greatest promise of success over other processes. In 1888 the Board of State Harbor Commissioners reported as follows: "The Board has given much attention to the various methods for the preservation of piles and timber from the ravages of the teredo and limnoria. The engineer of the Board is emphatic in his opinion that thorough creosoting is the best remedy that has so far been used for this purpose, and reports that this has been demonstrated both in Europe and this country."

In 1889 the Southern Pacific Company treated about one thousand piles at its temporary creosoting plant at San Pedro, the injection of creosote being about fourteen pounds per cubic foot. These were driven in Oakland Long Wharf in the next year and remained in the structure in excellent condition until it was removed in 1919. Many of the piles removed were redriven elsewhere and are still in serviceable condition after thirty-four years of exposure to date. A complete report of these piles is given in Proc. Amer. Wood Pres. Assn., 1920. In 1890 the Southern Pacific Company built a permanent creosoting plant at Oakland where it has subsequently treated all its piling for marine structures.

In that same year the sea wall north of Market Street was completed, practically closing out the area of what had been Yerba Buena Cove. Recalling that the first wharves of this region were started in 1849, it follows that the maximum economic life of such structures was forty-one years. However, the reclamation of the cove had caused the advancing fill to cut off the early portions, so that the actual economic life of those structures forced to cease operation because of the seawall was much less —probably about twenty years.

In 1895 a boiling method for the rapid artificial seasoning of piles with creosote, followed by pressure impregnation with that preservative, was patented by Mr. John D. Isaacs and Mr. W. D. Curtis. (See Proc. Amer. Wood Pres. Assn., 1917, 77.) Some thirteen thousand piles so treated were driven in the next few years in the Southern Pacific Company's Long Wharf. Most of these were likewise found in good condition, as were the one thousand from San Pedro, when the structure was removed in 1919.

In the same decade, beginning 1888 to 1890, which witnessed the extension of the creosote treatment of wooden piling, appeared the first crop of the superficial pre-

servative methods, classed together as the "paint and batten" methods. That the great expense involved in the construction of a creosoting plant, and in the process itself, has been a primary factor in limiting its use is illustrated by the following notation of the Harbor Board in 1890: "The Board has not yet felt justified in incurring the expense of a costly creosoting plant without further experiments. To this end, various preparations of asphaltum, limestone, canvas, burlap, ship felt, etc., have been thoroughly experimented with." Among such in 1889 the Fremont Street wharf was built with piles protected by the "Key West Pile Armor," a paint and canvas covering. In 1894, piles protected by the "Rood Process," known also as "Perfection Piles," were installed on the San Francisco waterfront, and other installations were made with the "Vulcan Pile Armor" and the "Paraffine Process." Experiments were also made with other ideas such as the "Built-up Pile."

In connection with the old Fremont Street wharf the "Cyrus Wakefield" incident has received such attention in some quarters that it requires mention. In 1892, which it will be seen was only three years after the wharf was built, the ship "Cyrus Wakefield" was moored to this wharf when, a storm arising unexpectedly, the ship towed a portion of the structure out into the bay. A chronicler of the time states, "An examination showed that the piles were entirely destroyed by teredo."—again showing the early tendency to call all borers of the shipworm type "teredo," although the destroyer of the Fremont Street wharf was almost certainly the giant shipworm, *Bankia setacea*, at least insofar as the destruction was of shipworm origin and not the much more easily observable work of the *Limnoria*. To the latter there is no reference in the contemporary accounts of the incident.

The year 1895 saw the introduction of concrete as a substructure material, concrete being first used as a casing for wooden piles instead of itself as a primary material for piling fabrication. In that year were completed the foundations for the new Ferry Building, in which clusters of untreated timber piles totalling about five thousand two hundred were encased in rectangular concrete piers constructed in open coffer dams. In 1896, the Pacific Street wharf, Pier 7 (present Pier 5) and the Folsom Street wharf (Pier 12, removed in 1915), were built with substructure units consisting of clusters of three untreated timber piles encased in concrete placed inside a cylindrical shell of $\frac{3}{16}$-inch boiler plate, the cylinders extending from a point just below mud line to the wharf level. Those in the former wharf are still serving after twenty-nine years.

For many years, this and similar types of mechanical armor were considered the final and permanent solution of the substructure problem. From the multitude of unsound or inadequate methods and proposals for making wooden piles everlasting—which then, as now, beset the user of piling—failures were inevitable. Moreover, there was then obtained a current average life from creosoted piling of only ten years. These results were due to lack of understanding of the reduction in efficiency and in life wrought on superficial piling protections by storm and other abrasion, and on both them and creosoted piles by injury from dogging and pike poles and by cutting and framing after treatment. Thus chemical wood preservation was unduly discounted and mechanical armors or shells of materials immune from borer attack and capable of surviving the rigors of marine exposure were considered by the Harbor Board to be the only positive protection for timber. While use of all types continued in varying degrees, the mechanical armor received greatest favor by the Board for a considerable period from this time on.

The Harbor Board's report for 1898, however, still contained the familiar statement: "The preservation of piles and timber is the one overshadowing question in the administration of waterfront affairs." In the same report the engineer of the Board

made the following significant comment: "All authorities in writing on the preservation of piles for marine work seem to ignore the existence of the *Limnoria terebrans*. In my opinion, it is much more destructive on this coast than is the teredo, and while a pile that has been thoroughly creosoted will resist the teredo, even if somewhat checked, the limnoria will find the slightest opening and destroy the pile."

In 1900, Pier 10 (removed in 1915) was built with three-pile concrete cylinder substructure units, similar to those of piers 7 and 12 mentioned above, but in which timber casings were used instead of steel. This type was developed and patented by Mr. H. C. Holmes, Engineer of the Board, and became known as the "Holmes" cylinder. In 1901 the Spreckels Sugar Refinery built a wharf with such a substructure, which is still serving after twenty-four years. In 1904 the Harbor Board reported as follows: ". . . the life of a dock constructed of preserved piles is about ten years . . . but with the advent of the cylindrical pier constructed of concrete, it looks as though a revolution has been made in the construction of docks and that the foundation is secure for an indefinite period. The oldest wharf (Pier 7) constructed under the new process . . . is ten years old and shows absolutely no deterioration. We have eight cylindrical docks. The aim of the Commissioners is to construct no other kind of pier . . ."

In that same year the continuation of the seawall south of Market Street was made possible by a bond issue and work was started. Fourteen years had elapsed since the portion north of Market Street had been finished, and during this time considerable doubt had been raised that it would ever be continued. Wharves had existed in the southern section for fifty years (fig. 6) before the final plan of development became a certainty.

In 1907 the Southern Pacific Company completed the Dumbarton Bridge across the south end of the Bay. This structure includes six 180-foot and two 40-foot steel spans, one 310-foot swing span and 6,375 feet of timber trestle approaches, constituting a total length of 7,845 feet. The steel spans are supported by concrete cylinder piers fifty-five to seventy feet high; the trestles are of cresoted timber piles, some of which are one hundred and twenty-five feet long. Of these, the piles in shallow water—about one-half of the total—were encased in concrete jackets in 1919 to protect them from marine borers.

The condition of wharves on the San Francisco waterfront was reviewed in 1908 by the engineer of the Board as follows: "There are practically two kinds of piers in existence on the waterfront of San Francisco. One is the pier resting on creosoted piles and comprises the remains of the old work, completed previous to the use of the Howard Holmes patent. The other comprises the piers resting on piles protected by concrete according to Mr. Holmes' patent . . .

"Those of the first kind are very hard to maintain, and it has been the policy of the Board for a long time to construct all new piers on the patented piles . . ."

However, he added: "In a few instances the concrete cylinder piers have failed and fallen from their positions. This latter failure is undoubtedly due to the practice of placing the concrete for a considerable portion of the bottom of the cylinders under water without any special device to prevent a separation of the ingredients." The failure was undoubtedly due, not only to this faulty construction, but to the fact that the concrete was not carried down far enough into the mud to prevent exposure of the pile when scouring of the bottom removed the mud and thus opened the way for borer attack. Thus one more type in which great hopes had been placed was showing signs of not being the "permanent solution." The instance is given in detail because it shows, as in many similar cases, that the failure was due less to any inherent fault

of the type than to faulty construction or application of the method. It is safe to say that many of the "failures" could be successful if faulty workmanship and application could be avoided.

THE MODERN PERIOD: IMPROVED PRACTICE IN ALL DIRECTIONS

In the decade beginning in 1908, attention continued to be focussed on the possibilities of concrete in one form or another, culminating in the present day use of reinforced concrete; but its latter half also saw a return of creosote to popular favor for marine structures.

In 1908 a modification of the Holmes cylinder was developed which in part eliminated some of the difficulties previously experienced. In this type the three-pile cluster was replaced by a single pile, encased in concrete. With the single-pile type it was possible in construction to place around the pile a gasket which sealed the bottom of the form, after which the form could be pumped out and the concrete poured properly. This type has given excellent service to date.

The Koetitz form of precast concrete casing for timber piles was also developed in 1908. In this type the casing is cast on land and, after curing, is slid over the previously driven pile, in place, the space between being filled with sand or grout. This protection has proved very successful, although never extensively used on account of rather high cost. Another development of the year 1908 was the Black's Patent, which was the forerunner of several forms of pile repair now used for salvaging piles in place, by pouring around each a concrete jacket, section by section, without contact with surrounding water until after the concrete has been poured. That same year there was introduced also a substructure unit in which piles were omitted, consisting of a reinforced concrete column cast in place in a large cylindrical coffer dam previously driven to hard bottom and pumped dry. In both types the forms were afterwards pulled and used elsewhere. The latter type could only be used where the distance to hard substrata was within the practical limit in length of the cylinder forms. With the exception of minor defects, the type has given good service.

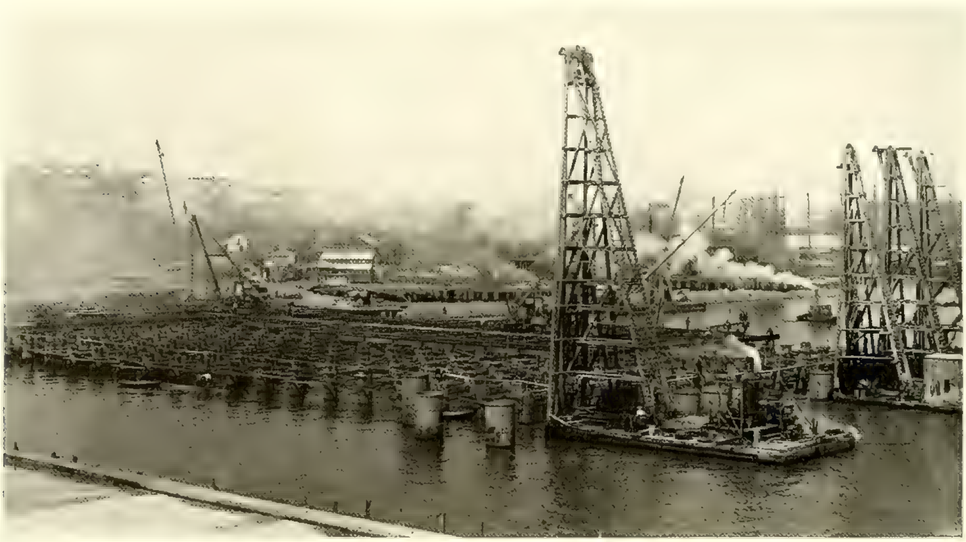

Fig. 10. Driving cylindrical cofferdam forms, pier 36, August, 1909.
(Board of State Harbor Coms. Photo.)

In 1909 the design for subsequent seawall construction was changed from the loose rock type to include a core wall of mass concrete supported on piles. This was done to provide a definite bearing for structures to be built on the wall, thus avoiding the settlement which steadily continued in the loose rock type; the piling furthermore added stability to the seawall and served to fix the rock in a more compact mass.

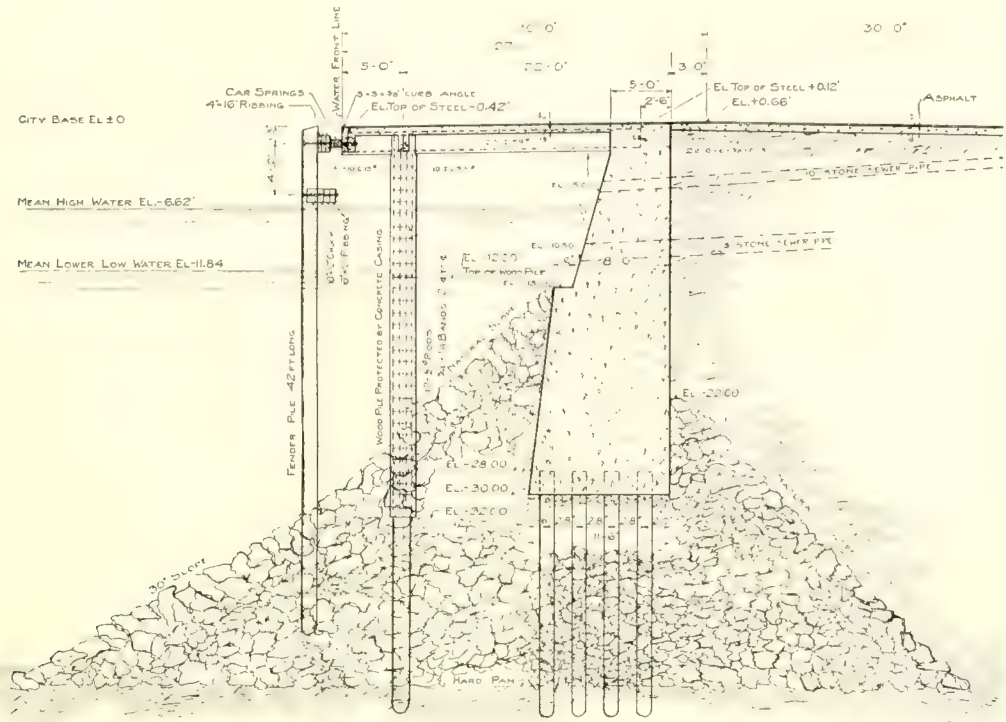

Fig. 11. Cross section of seawall.
(*Board of State Harbor Coms. Photo.*)

That same year an experiment was made with twelve hundred piles of untreated Eucalyptus, for which high claims had been repeatedly made, to ascertain their ability to withstand borer attack. They failed very rapidly and were removed in a few years.

In 1911 reinforced concrete piles were introduced in structures both in San Francisco and Oakland. This type has since been used successfully in numerous structures, although insufficient time has elapsed to judge its ultimate life.

In 1912-1913 a biological survey of the Bay was made by the United States Bureau of Fisheries, cooperating with the University of California. It is of interest that no *Teredo navalis* was found in the survey, indicating either that it had not arrived in the Bay or was present only in small, isolated numbers.

In 1914 the Harbor Board reported that the three-pile concrete cylinders had for the most part proved "costly failures." In six piers these cylinders had failed in from seven to fifteen years. They had cost about three times as much as creosoted piling without giving any longer life. Thus the latter type was once again reinstated to the position it had formerly occupied. In the next two years six piers were repiled and nine new piers constructed with creosoted piling. Meanwhile, hope for a solution of the problem in the direction of concrete was transferred to reinforced concrete piles,

the reinforced concrete columns bearing directly on substrata without pile supports, and to the Koetitz pre-cast type of sleeve protection for wooden pile protection. Attention was also given to the development of wharf design whereby each available type of substructural material could be used to best advantage.

Up to this time the Bay region at the north, toward the great fresh water influx from the Sacramento River, had supposedly been free of borer infestation. The Carquinez Strait territory had become extensively developed by industrial and transportation enterprises, and wharf construction had increased accordingly. All the wharves were of untreated timber, portions of some having been built as far back as 1870, and all were apparently unmolested.

The first discovery of *Teredo navalis* in the Bay came, as has been briefly related in the introduction, in 1914 when a borer later identified as this species was reported active in a structure at Mare Island. There was also some evidence that it had been there in 1913. Subsequent demonstration that this borer could thrive in the brackish water of the region and that conditions had long prevailed favorable for its attack without such attack taking place, led to the conclusion that 1913 was the year of its arrival in the Bay. A period of higher rainfall (see chart, p. 37) in the next three years—1914 to 1917—increased the fresh water river flow and reduced the salinity in the upper Bay, killing off the borers or temporarily preventing further attack. However, while the *Teredo* was thus checked in the northern territory, the infestation spread to all parts of the Bay where higher salinities prevail, thus adding this borer to the existing *Bankia* and *Limnoria* infestations. Structures in those regions were by this time, for the most part, built of protected piling, so that the coming of the teredo had no marked effect.

The year 1917 was one of low rainfall and the salt water of the Bay once more advanced up the northern tributaries. This condition was further accentuated by the withdrawal of large quantities of river water for municipal supplies, for rice culture

Fig. 12. Untreated ferry slip fender piles in Carquinez Strait destroyed by teredo, 1919. (*S. P. Co. Photo.*)

and for general irrigation projects which had developed in recent years. Renewed teredo attack was soon reported at Mare Island, but little attention was given to it elsewhere. This apathy was largely due to the fact that no trouble had been experi-

enced before in the region. In the Bay proper the presence of borers is soon disclosed by *Limnoria* attack on the pile surface; but in the upper region the salinity is too low for that borer and since the teredo attacks the interior of piling, without visibly affecting the exterior surface, the exposed timber showed no outward signs of a serious condition.

While the rainfall was somewhat higher in 1918, the infestation remained and spread to all parts of the region. This prepared conditions for the great destruction of wharves in 1919. In that year the rainfall was less than it had been for over forty years; it has been estimated that the river discharge was less than it had been since 1863. It is likely that all the wharves had been weakened by the attacks of the two previous years, and the invasion of 1919 completed the destruction. In the fall months of that year, at the close of the breeding and settling season, wharves began to col-

Fig. 13. Untreated Douglas fir piling in Oakland Estuary, destroyed by Limnoria. Good piles shown are replacements. (*Moore Shipbuilding Co. Photo.*)

lapse, and this continued throughout the following year. Impact of ships which would ordinarily be resisted by flexure of the piling, now caused the latter to break off in large groups; vibration from various impact loads produced the same result; in some cases the wharves collapsed of their own dead weight. The destruction affected about fifty structures with a damage estimated at $15,000,000.

This led to the organization of the San Francisco Bay Marine Piling Committee, as has already been related. The epidemic destruction continued practically as long as the supply of untreated wooden pile structures lasted, until, by the end of the year 1921 the bulk of structures with untreated piling had been destroyed, and the damage thus caused amounted in money value to at least $25,000,000.

Destruction from marine borers in San Francisco Bay has been most active in the regions nearest the Golden Gate, where unprotected timber is destroyed within a

few months. Destruction is nearly as rapid southward around the San Francisco waterfront, but on the Oakland side is generally somewhat less rapid, unprotected piling lasting from 18 months to three years. In the Oakland estuary the activity of *Limnoria* is greater than that of *Bankia*, and piling is not destroyed in as short a time as it is nearer the Golden Gate (fig. 13). From South San Francisco on the western side of the Bay and Alameda on the eastern, there is, southward, a vast stretch of shoreline enclosing the southern end of the Bay, which is its largest area. Industrial activity of a kind which requires waterfront construction is very scanty, however, in this southern area. There are, therefore, few structures from which the activity of borers may be measured. On account of the much greater industrial importance of the northern areas a complete study of the southern area was not attempted. Some investigations, however, were carried as far south as the Dumbarton Cut-off. At the plant of the Schaw-Batcher Company in South San Francisco, there was found an attack by *Teredo diegensis*, a species of teredo not observed during this survey in the northern part of the Bay area. This will be discussed in the biological section of the report.

In the northern area, including the lower course of the Sacramento River, Suisun Bay, Carquinez Strait and the adjacent portions of San Pablo Bay, where the de-

Fig. 14. Untreated ferry slip fender piles in Carquinez Strait, destroyed by *Teredo* in 1919. (*S. P. Co. Photo.*)

struction since 1917 by the teredo has been so swift and so unusually severe, every waterfront structure as far upstream as Antioch has been attacked by the teredo. Following is a list of the more important structures which have suffered most severely from the borers in that area:

HERCULES

Fernandez Wharf.

Hercules Powder Co.

RODEO

6-Minute Ferry.

OLEUM

Union Oil Co.

SELBY

American Smelting & Refining Co.

Vallejo Junction
- Southern Pacific Co. ferry.

Black Point
- Northwestern Pacific Railroad bridge.
- State Highway bridge.

Mare Island
- U. S. Navy structures; dykes (one 8000 feet long), docks, and causeway (3500 feet long).

Napa Junction
- Associated Oil Co.

Vallejo
- Ferry to Navy Yard.
- Southern Pacific Co. ferry.
- San Francisco, Napa & Calistoga Railroad.
- Monticello Steamship Co.

South Vallejo
- Ferry to Rodeo.
- Southern Pacific Co. ferry.
- Sperry Flour Co.
- 6-Minute Ferry to Crockett.

Crockett
- Port Costa Lumber Co.
- Matson Navigation Co.
- 6-Minute Ferry.
- California and Hawaiian Sugar Refining Co.
- Banker's Warehouse.
- Fort Bragg Dock.

Port Costa
- Granger's Warehouse.
- McNear Warehouses.
- Southern Pacific Co. ferry and other structures.
- Associated Oil Co.

Benicia
- U. S. Shipping Board pile boom.
- Southern Pacific Railroad ferry.
- Municipal wharf and ferry.
- Southern Pacific Co. river boat docks.
- G. W. Hume & Co.
- Kullman-Salz Co.
- U. S. Arsenal piers.

Martinez
- Municipal wharf and ferry.
- Shell Co. of California.
- American-Oriental Oil Co.
- Mountain Copper Co.
- Electrolytic Zinc Co.
- General Chemical Co.

Avon

Associated Oil Co.

Bay Point

Pacific Coast Shipbuilding Co.
Coos Bay Lumber Co.

Mallard

San Francisco-Sacramento Railroad ferry.

Chipps

San Francisco-Sacramento Railroad ferry.

Dutton

San Francisco-Sacramento Railroad trestle and drawbridge.

Pittsburg

Small docks.

Antioch

Muncipal dock.
A. T. & S. F. R. R. dock.

Returning to construction progress in the Bay region, in 1919 a change in the Government pierhead line at Oakland caused the removal of the Long Wharf extension, originally built in the years 1869 to 1871 and rebuilt in the years 1890 to 1900 with creosoted piling. Most of this piling, totalling a large amount, as has already been stated, was found in excellent condition at the date of its removal.

In 1921 an extensive program of piling inspection by diver, and of repair work, was completed on the San Francisco wharves of the Board of State Harbor Commissioners. This investigation disclosed the remarkable fact that eighty per cent of the pile flaws attacked by *Limnoria* had been caused by the careless driving of pile dogs or pike poles in sections falling below the water level, the holes not having been plugged after the dogs were pulled; about fifteen per cent were in checks developed during or after driving, and the balance were from miscellaneous defects.

The year 1922 saw the completion of the seawall around the southern portion of the San Francisco front from Market Street to China Basin, enclosing the area where wharves had existed since the early 50's. The old Mission Street wharf No. 1 had, with reconstruction and relocation, been in service from 1853 to 1909, or fifty-six years; Howard Street wharf No. 1, built in 1865, was removed in 1914 after forty-nine years of service; the Pacific Mail wharf, built in 1866, was removed in 1907 after forty-one years of service. During the period from 1904 to 1922 in which the south section of the wall was built, there had also been constructed seventeen new piers projecting from the new wall, replacing practically an equal number of old wharves, such as the three mentioned above, which had been built to conform to the old waterfront plan.

In 1922 work was started on o e of the largest of San Francisco harbor projects, the China Basin Terminal. The substructure on the water side consists of a series of rectangular concrete piers 7.5 feet thick, 20 feet wide and from 54 to 57 feet deep. They are connected at the top by pre-cast, curved, reinforced concrete arch slabs to form the wharf floor support, and on the inshore side by similar slabs to form a retaining wall for holding back the foundation fill. The piers were constructed on shore as reinforced concrete caissons, after which the ends were sealed and the caissons floated to the site. They were then sunk into position bearing on hardpan and fifteen

piles were driven in each. Finally they were pumped dry and filled with concrete, and the pre-cast curved arch slabs then placed in position. (See p. 133.)

In 1923 work was started on the Carquinez Highway Bridge across Carquinez Strait near Crockett. This structure, which was completed in May, 1927, consists of two main spans 1100 feet long, a central tower pier 150 feet wide, and a 500-foot anchor span on either end, giving a total length for the main bridge structure of 3350 feet. The substructure consists of concrete piers which cost about $2,000,000. These piers are constructed in coffer dams carried down to rock, the two largest extending 140 feet below mean high water level. The total cost of the entire project was about $8,000,000.

The year 1924 was one of exceptionally low rainfall, which was even less than in 1919, with the result that the salt water advanced further up the rivers than ever before recorded. In doing so it carried the teredo infestation in the Carquinez Strait beyond the region of heavy attack of 1919-1920 to points where unprotected piling

Fig. 15. China Basin terminal during construction, showing caissons after filling (workman whose hands are blurred is standing in one) and pre-cast curved arch slabs in place.
(Board of State Harbor Coms. Photo.)

still existed. Wharves which had previously been practically unmolested were severely attacked. Even when the coming of the borers was carefully watched and plans made accordingly for reconstruction, their progress was in some cases so rapid that, before new materials could be assembled, structures were weakened to an extent such that they were unable to withstand unusual impacts from vessels. Disasters coming thus in spite of attention being given to the conditions illustrate the jeopardy involved in wharves located in regions of marginal salinity between fresh and salt water.

Another transbay structure, the Dumbarton Highway Bridge, has just been completed across the south end of the Bay, extending from San Mateo due east to the opposite shore a short distance north of the present Southern Pacific Company railroad bridge. The new bridge includes eight 226-foot steel spans, one 228-foot steel

vertical lift span and about 4,270 feet of approaches, or a total length of 6,306 feet. The steel spans are supported on concrete piers and the approaches on reinforced concrete piles. The entire structure cost about $2,000,000.

Projects for other large bridges across the bay and the Golden Gate are actively promoted but are not yet sufficiently crystallized to warrant their discussion here. The city of Oakland has voted $9,000,000 to begin the development by that municipality of adequate commercial wharf and terminal facilities on its extensive waterfront. No construction details have yet been given out, however.

In conclusion, the gradual adoption of protected substructure materials has been accompanied by the establishment of modern wharf facilities throughout the Bay. The Port of San Francisco has been developed to a point where its facilities rank with

Fig. 16. Carquinez Bridge during construction. California and Hawaiian Sugar Co. plant (location of test station C) is behind approach at right side.
(Photo by courtesy of American Toll Bridge Co.)

the foremost of the United States. In the course of time a vast number of substructure materials and methods has been tested, but the field of successful survival is narrowing down to a comparatively few. These, however, supply a sufficient variety to fit most conditions. Means have been developed for the practical use of timber, of timber combined with other materials and of substitutes for timber. If no radically new materials or methods have been brought to light by this investigation, it has added knowledge respecting both the possibilities and the limitations of present materials and methods which now makes it possible to build and maintain marine structures better than in the past and adequate for all economic requirements.

HYDROGRAPHIC SECTION

By C. E. Grunsky

CHAPTER III

GEOGRAPHY AND HYDROGRAPHY OF SAN FRANCISCO BAY

GEOGRAPHY OF THE BAY AND ITS TRIBUTARY REGION

The waters of the San Francisco Bay system are made up of three more or less distinct areas, as shown by the frontispiece map, known as San Francisco Bay, San Pablo Bay and Suisun Bay. While the name "San Francisco Bay" is technically applicable only to the larger and more important southern arm of the body of water which has its connection with the Pacific Ocean through the Golden Gate, that name is more often used than any other when it is desired to indicate the entire body of water. This total bay area has its longer dimension closely parallel to the sea coast. It is 52 statute miles in its greatest length in a single direction, and has a maximum width of slightly under 12 miles. The outlet through the Golden Gate is at a point about three-fifths of the total length of the bay from south to north. At a point about one-half of the remaining distance north from the Golden Gate the width of the bay is reduced to a little over one mile, and that point marks the division between San Francisco Bay proper and the upper area known as San Pablo Bay.

At the eastern end of San Pablo Bay there enters a channel known as Carquinez Strait, through which the combined flow of the Sacramento and San Joaquin Rivers is discharged into San Pablo Bay from Suisun Bay. The Carquinez Strait is from seven to eight miles in length. Suisun Bay is a large area of water bordered by many tidal flats and salt marshes. At the head of Suisun Bay is the junction of the Sacramento and San Joaquin Rivers. Above that junction both rivers meander in constantly dividing and re-uniting channels, through an extensive delta region of islands, sloughs and marshes.

The water surface of these bays is not delimitable with perfect accuracy. It will suffice to say that, at ordinary high tide (not including tide marsh lands), it has an area of about 460 square miles. This area is made up of the main San Francisco Bay, 288 square miles; San Pablo Bay, 112 square miles (see University of California Publications, Vol. 14, No. 1, p. 20, Albatross Surveys); and Suisun Bay, about 60 square miles.

The Golden Gate, through which the San Francisco Bay is connected with the ocean, is the narrows between Lime Point on the north and Fort Point on the south. Oceanward from the Golden Gate is the outer bay. This is hemmed in on the north by the cliffs of the Marin shore which end their concave sweep at Point Bonita and on the south by the bluffs of the San Francisco shore which have their westerly termination at Point Lobos.

Through this outer bay and through the Golden Gate, which is less than a mile in width, there is a tremendous tidal flow, which has cut and holds the gorge near its narrowest point to depths of more than 300 feet.

Some five miles beyond the Heads, as Point Lobos and Point Bonita are commonly called, lies the bar. Here is the crescent shaped crest of a great sand-bar, subject to

change under the ever varying forces of nature and yet so little altered in the half century during which it has been repeatedly surveyed that no characteristic or predominating tendency to change has yet been discovered.

The watershed area tributary to the Golden Gate is about 62,000 square miles. Of this area 2014 square miles are tributary to the main or south arm of the bay; 964 square miles are directly tributary to San Pablo Bay; 557 square miles are in the watersheds of small streams discharging into Suisun Bay; 58,000 square miles are embraced within the drainage basins of the Sacramento and San Joaquin Rivers, which discharge into the upper end of Suisun Bay; and 460 square miles, as above noted, are bay water surface.

TIDES AND THE TIDAL PRISM IN RELATION TO FRESH WATER ACCESSION AND SALINITY

Concerning the tides in San Francisco Bay the late Prof. Geo. Davidson, in the "Pacific Coast Pilot," says:

> "From the lower low water (low water large) the tide rises for about 7¼ hours, say 4.4 feet, to the smaller of the two high tides (high water small); then falls 1.4 feet in less than 4½ hours to the 'low water small' which is higher than the preceding low water; then rises, say 2.9 feet in 6¼ hours to the higher high water or 'high water large'; it then falls again 5.8 feet in over 7 hours to the lower low water, or 'low water large.'
>
> "Instead of the above figures, the fall from high water small or 'half tide,' to the 'low water small,' may range from 3½ feet at one position of the moon to 0.3 feet at another; in the latter case there will be apparently a long stand of about 5 hours. . . .
>
> "The average difference of the higher high and lower low waters of the same day is 5.2 feet, with a greatest observed range noted for February 8, 1876, of 9.93 feet."

Careful studies were made by the late Dr. G. K. Gilbert of the tidal movement in San Francisco, San Pablo and Suisun Bays,* as the result of which the following may be noted:

The average volumes of great tropic ebb currents, as dependent on the effective tidal prisms of bays, other bodies of open water and marsh tracts, are estimated by Dr. Gilbert as follows:

At Golden Gate, 91,948,000,000 cubic feet or 2,110,000 acre feet.

At San Pablo Narrows, 39,800,000,000 cubic feet or 910,000 acre feet.

At Carquinez Strait, 20,580,000,000 cubic feet or 470,000 acre feet.

He gives the following as the effective ranges of tide (great tropics):

In Golden Gate, 6.2 feet.
In San Pablo Bay, 6.2 feet.
In Carquinez Strait, 7.2 feet.
In Suisun Bay, 7.3 feet.

The Sacramento and San Joaquin Rivers, the drainways of the Great Central Valley of California, meet at Collinsville at the head of Suisun Bay. This Bay is of particular interest at this time because it is, at low stages of the rivers, the principal mixing pool of river and ocean waters. Its tidal area under natural conditions was larger than now by about 100 square miles of marsh lands, formerly submerged at

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*See Professional Paper No. 105, U. S. Geological Survey, "Hydraulic Mining Debris in the Sierra Nevada," by Grove Karl Gilbert.

high tide but now to a large extent reclaimed, lying principally along its northern shore. The volumetric contents of Suisun Bay are about 480,000 acre feet at low tide and about 700,000 acre feet at high tide, and the volumetric contents of San Pablo Bay are about 1,000,000 acre feet at low tide and nearly 1,500,000 acre feet at high tide. These volumes of water are pushed back and forth by the tides, becoming more salty during the protracted annual low water stage of the rivers and freshening again to a greater or less degree as the rivers rise to their winter and spring high stages.

For a tidal range of 6 feet at the upper end of Suisun Bay, when the rivers are at their low stages, that is, generally from some time in July to November, the volume of water which is required to fill the tidal prism in the lower reaches of the Sacramento and San Joaquin Rivers may be noted approximately at 57,000 acre feet for the San Joaquin River and 25,000 acre feet for the Sacramento River. The discharge of the rivers, when material, during the time interval between the extremes of tide, must, however, be given consideration if a comparison is to be made between the volume of flood flow from the bay which is required to fill this tidal prism and the volume of water delivered into the bay from the rivers on the ebb flow. The river discharge decreases the volume of water moving up-stream on the flood tide and increases the volume of water moving down-stream on the ebb tide. Variations in the volume of river discharge are therefore reflected inversely in the salinity of water in areas subject to both influences.

In seasons of substantially normal weather the discharge of the rivers into the bay increases in September or October from its low summer stage, from various causes: there is then a decrease in the evaporation from the water surface of the rivers and delta channels, there is a decrease in the irrigation draft, and the winter rains begin about that time of year. The water of Suisun Bay, which is brackish in the summer and fall, is gradually freshened, therefore, by the increased stream flow which then begins. In the year 1920, when the teredo epidemic reached its height, and which was a year of very low river stage in summer and in the early fall, the waters of Suisun Bay reached their maximum salinity about the middle of September and, a few weeks later, particularly after the winter rains commenced, the increasing flow of the rivers accelerated the freshening of the water in the upper end of Suisun Bay, so that by the middle of November the brackish water had there been displaced. The seasonal rainfall at the end of December (July 1 to December 31, 1920), was about 40 per cent in excess of the normal. At the time of greatest salinity during that year, the bay water at Collinsville, just below the mouths of the two rivers, at high tide slack water, was about one-half ocean water; and at low tide slack water somewhat less than one-third ocean water.

Some evidence was presented in the recent Antioch case, to the effect that about 1869 or 1870, under then prevailing conditions before extensive reclamation works had been carried out, the presence of bay water was noticeable by brackish taste as far up stream as Three Mile Slough in the San Joaquin River. The presence of brackish water at Antioch, brought up from the bay by the flood tides in the fall months, seems to have been frequently noted, and its presence there in sufficient quantity at certain times in past years, before the question of the effect of the reduction of river flow by the irrigation draft was raised, is evidenced by the very general use of cisterns by the residents of Antioch. In these cisterns, some of which have been in use 30 years or more, water obtained from the river in the spring of the year, when the river at Antioch is fresh at all tides, is held for domestic use later in the season.

PRECIPITATION, FLOOD HABITS AND WATER DELIVERY, SACRAMENTO AND SAN JOAQUIN RIVERS

Some idea of the relative amount of fresh water reaching the bay region can be obtained from the rainfall records, if the fact is borne in mind that run-off is not proportional to rain, but that in wet years, that is in years of much rainfall, the portion thereof which reaches the streams is larger than in dry years or years of light rainfall. The climatic years and not the calendar years are here referred to. A diagram is presented (fig. 17) showing the relative annual precipitation in central California since 1849, in per cent of the normal annual rainfall. The beginning of the climatic or seasonal year was taken at July 1st.

The normal annual delivery of fresh water into San Francisco Bay by the two principal rivers which discharge into the bay is approximately 35,000,000 acre feet. About 85 per cent of this water reaches the bay in the first six months of the year, and rather less than 15 per cent thereof in the last six months. Fig. 17 also shows the seasonal water output of Sacramento River, based on a summation of the discharges of the Sacramento River at Red Bluff and its principal tributaries at foothill points, not including Stony, Cache and Putah creeks, or other lesser tributaries. For the years preceding the period covered by records of the U. S. Geological Survey, the discharge for the climatic year has been approximated from rainfall and it has thus been possible to give the eye a picture of the relative amount of water annually discharged into Sacramento Valley by these streams for the full period of 70 years covered by rainfall records.

What is presented in the diagram, although applying to only a part of the area tributary to the upper end of the bay, being expressed in per cent of normal flow, may, nevertheless, be accepted for the present as fairly well representing the relative annual fresh water accession of the bay from both the Sacramento and the San Joaquin Rivers, subject, however, to some correction for greater diversion for irrigation in recent years than formerly.

The normal low water output of the Sacramento and San Joaquin Rivers at the point where they discharge into Suisun Bay, as it was before disturbance by human activities, is not ascertainable with any great degree of precision. In the early history of the State, measurements of the stream flow were not made, and now the effect of human activities upon this flow is material.

To give some idea of the amount and range of the annual water delivery into Suisun Bay by the Sacramento River, which delivers about four times as much water as the San Joaquin, table 1 has been prepared showing the flow of the river, by months, in selected recent years.

The figures presented in the table, being a summation of the discharges of Sacramento River at Red Bluff, of Feather River at Oroville, of Yuba River at Smartsville, of Bear River at Van Trent, and of American River at Fair Oaks, will give some idea of the normal discharge of Sacramento River and the range of its mean monthly discharge, all amounts noted being based on the estimates of the U. S. Geological Survey.

Not only should the facts relating to the variation in the seasonal delivery of water by the rivers into the bay be given consideration when the degree of salinity in different years is compared, but it is likewise important to bear in mind that the mean monthly discharge of the rivers from the mountains into the valley varies within wide limits. The natural normal combined flow of the two rivers for the several months shows a range from a minimum monthly mean of about 7000 second-feet to a maximum of about 70,000 second-feet, while in certain individual years the range

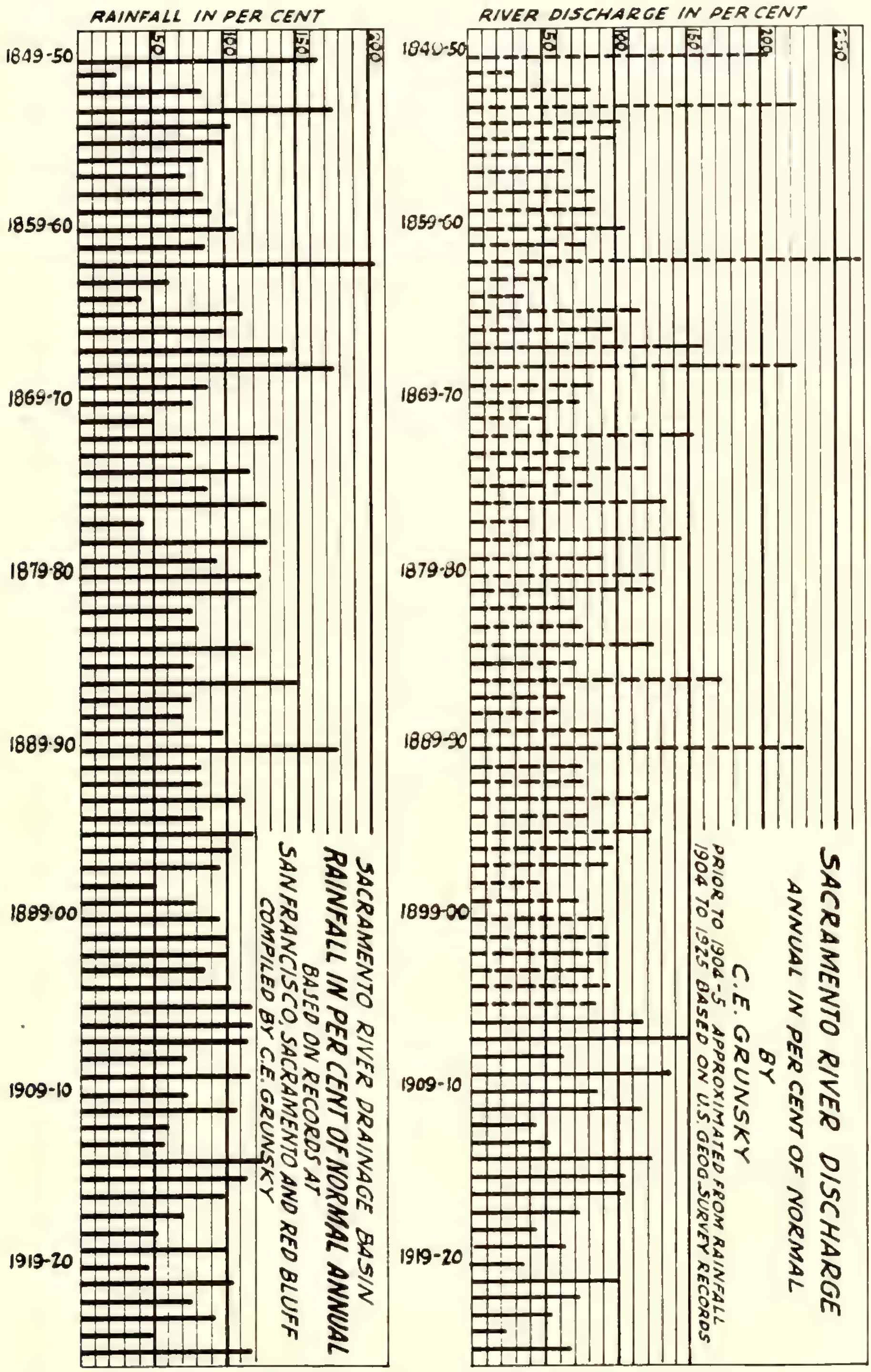

Fig. 17. Sacramento River discharge and rainfall in Sacramento River drainage basin.
(The normal discharge of the Sacramento River into Suisun Bay is about 35,000,000 acre-feet per annum.)

TABLE 1

Summation of Discharge of Sacramento River at Red Bluff and of the River's Principal Tributaries

MONTH	Normal discharge sec.-ft. Rain 93%	SEASONS OF LIGHT RAINFALL 1911–12 sec.-ft. Rain 59%	1912–13 sec.-ft. Rain 56%	1918–19 sec.-ft. Rain 101%	1919–20 sec.-ft. Rain 45%	A flood year 1906–07 sec.-ft. Rain 116%
October	7,850	7,616	6,631	9,528	6,934	8,188
November	10,600	8,195	15,937	9,910	6,515	9,751
December	17,300	7,914	11,585	10,006	10,024	31,480
January	45,744	17,870	24,990	18,009	7,930	39,070
February	51,751	14,721	16,368	53,560	8,138	98,610
March	53,794	23,026	18,853	38,650	19,270	139,050
April	51,975	21,102	39,126	47,940	29,820	91,700
May	43,908	37,027	36,319	36,186	24,218	60,254
June	26,800	21,261	15,742	10,850	10,984	45,532
July	11,679	8,188	8,339	6,908	6,371	22,205
August	7,605	6,319	6,642	6,201	5,365	11,186
September	7,194	7,530	5,872	6,182	5,035	9,086
Yearly mean	28,000	15,070	17,190	20,960	11,720	47,260

Note: The normal discharge of Sacramento River noted in table 1 is the average of the monthly estimates by the U. S. Geological Survey for the period 1905 to September 30, 1920. It is probably somewhat below the actual normal because there has been a preponderance in recent years of seasons with less than normal rain. The rain noted in the table is expressed in per cent of normal and is based on the records of rainfall at San Francisco, Sacramento and Red Bluff. The figures are used only to give an approximate indication of the relative amount of rain in the watershed of Sacramento River which produced the run-off.

has been much greater, as for example in the season 1906-1907 (see table 1). The curves shown in fig. 18 will give a fair idea of the river stages throughout the year in per cent of the normal mean annual discharge. The information is given in this diagram for Sacramento River and for both rivers combined.

Under natural conditions at flood stages the greatest momentary discharge of both rivers combined probably reached quite frequently 200,000 to 300,000 second feet. The Government project for flood control will withdraw from inundation the natural flood basins which flanked the rivers, or will materially reduce their areas. The retarding effect of these basins upon the flood volume will be eliminated or greatly reduced and the peak of the flood discharge will be raised. After this project is carried out, the Sacramento River alone may be expected, under conditions such as prevailed at the flood of March, 1907, to deliver some 500,000 to 600,000 second-feet at its extreme stages.

It is of considerable importance in the study of the habits of the Sacramento and San Joaquin Rivers, that the characteristics which are most marked today were faithfully described more than a century ago. From the Publications of the Academy of Pacific Coast History the following is quoted. Fray Narcissus Duran in his diary writes:

> "May 16, 1817. All along the Sacramento River it is like a park, because of the verdure and luxuriance of its groves of trees. Still, it is difficult to land, because everything is inundated, due to the rise of the river from the melting of the snow."

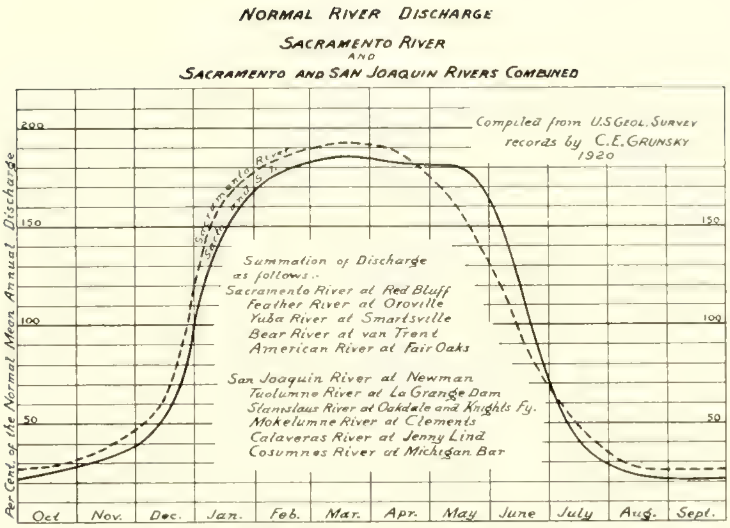

Fig. 18. Normal river discharge, Sacramento River and Sacramento and San Joaquin Rivers combined.

"May 19, 1817. (Continuing up the river near the site of Sacramento.) The river is much swollen and is flooded on both sides, so that one can scarcely alight upon land."

"May 24, 1817. At midday we set out to join the commandant at the strait of Chupcanes (Carquinez), which we reached at six o'clock in the afternoon, finding the said gentleman there; he had arrived in the morning. We traveled this afternoon as far as the mouth of the San Joaquin. It is necessary to pass this at high tide, because there is a sand bar, and the launches are blocked by it. There is this difference between the Sacramento and the San Joaquin; the latter carries less volume of water, although in some places it is wider; and in all that part which we have traveled there is nothing but tule, without a tree under which the navigator may find shade, nor a stick of firewood with which to warm himself; whereas the Sacramento, when it is not flooded, has dry land on both banks covered with poplar groves, as has been said, and it seems to carry a greater abundance of water."

Commander Cadwalader Ringgold, U. S. Navy, reported his observations and surveys of 1849 and 1850. On page 39 of his report, the following important fact is stated:

"At the lowest stages of the water, the maximum depth available for vessels proceeding up the Sacramento River, owing to the obstructions existing in portions of the channels, does not exceed ten feet; from six to eight in the San Joaquin River."

MODIFICATIONS OF RIVER REGIMEN BY HUMAN ACTIVITY

The regimen of the two large rivers which discharge into the upper bays has been materially modified by human activities. Hydraulic mining contributed enormous amounts of sand and sediment to the natural sediment load of the two rivers—more particularly to that of the Sacramento River. It is not proposed to discuss this problem fully. It will suffice to call attention to the fact that under original conditions,

tidal influence extended up Sacramento River as far as Sacramento. The tidal range was there in excess of 2 feet and extreme low water fell at times below the zero of the Sacramento gage, which is 0.48 foot below mean sea-level. Under the effect of hydraulic mining the bottom of the river was raised by sand deposits and the rising bottom forced up the water surface of the river so that the lowest low waters of the years 1895-1899 averaged about 8 feet higher than those which prevailed originally.

In recent years the bed of the Sacramento River has again been lowered to near its original position. The principal causes which have contributed to this depression of the river bed are the cessation of hydraulic mining on a large scale; the restraining of mining debris under Government direction at or near the mines; the extensive dredging operations carried on in the rivers to secure material for river levees, and to enlarge the lower reaches of the river; and the scouring action of the river, which is better confined between the river levees in recent years than theretofore.

The changes which have occurred in the low water elevations at Sacramento are well illustrated by the following figures from gage readings at Sacramento:

TABLE 2

LOW WATER AT SACRAMENTO

GAGE READINGS AT LOWEST STAGE OF TIDE

Period	Average of annual lowest gage readings	Period	Average of annual lowest gage readings
1849–53	0.3	1889–93	7.7
1854–58	1.0	1894–98	7.9
1859–61	1.6	1899–03	7.2
1862–73	no record	1904–08	6.8
1874–78	5.3	1909–13	4.4
1879–83	6.7	1914–18	3.2
1884–88	7.3	1919–20	0.4

As the destructive work of the teredo in the upper bay region apparently did not become serious until within the two or three years preceding 1920, it is of particular interest to note the fact that the climatic year 1917–18 was a year of very light rainfall and small run-off (see fig. 17); that the rainfall of 1918-1919 in aggregate amount was about normal at San Francisco and Sacramento but that it was so distributed in time that it produced materially less than normal run-off from the watersheds of the Sacramento and San Joaquin Rivers, and that both rainfall and run-off for 1919-1920 were less than 50 per cent of normal.

During the low water period of these years the irrigation draft upon the Sacramento and San Joaquin Rivers was increasingly heavy, due largely to rice growing in the Sacramento Valley, and there was a period of several months of the year 1920 during which it seems to have been a fact that more water was used for irrigation on the delta lands of these rivers than was supplied to the delta channels by the two rivers. This, together with the maintenance of a flow in the lower river, was of course possible only by reason of subsurface return of a portion of such irrigation water to the river. In such circumstances some of the bay water which entered the mouths of the rivers on each flood tide was retained in the river channels and caused bay water, under the influence of tidal action, to get up stream at high tide to points in the Sacramento River somewhat above Isleton and in the San Joaquin River to points probably above the mouth of Middle River. The salinity records of the State Water

Commission show a chlorine content in the San Joaquin River at Blake's Landing (Venice Island) in September, 1920, of 56 parts in 100,000 at high tide and 40 parts at low tide, representing about 92 parts and 66 parts of common salt respectively. While a portion of this salt is probably attributable to the presence of some bay water, care is necessary in interpreting this information in view of the report of W. E. Allen on "A Quantitative and Statistical Study of the Plankton of the San Joaquin River and its Tributaries in and near Stockton, California, in 1913," in which he says on page 21: "In spite of the low water it is not at all probable that sea water ever had any influence here except in causing tides." He then notes the salinity of the river water at a point in the river from 400 to 800 yards up-stream from the mouth of Stockton channel at about 30 day intervals throughout the year. The highest salinity (uninfluenced by ocean water) was shown by the samples taken on November 22nd. The chlorine content of the water was then 66 parts in 100,000. This is equivalent to about 99 parts of common salt in 100,000 parts of water. The situation relating to the up-river penetration of bay water is aggravated by the fact that the work of channel enlargement on the Sacramento River below Rio Vista, in progress since 1913 and being done by the U. S. Government in cooperation with the State of California, has been a material factor in facilitating tidal flow in the lower reaches of that river and in augmenting the

TABLE 3

Range of Salinity in the Lower Reaches of Sacramento and San Joaquin Rivers and in the Head of Suisun Bay in 1920

Based on samples taken for the California State Water Commission at high and low tides. Salinity is given in parts of salt per 100,000 parts of water. (Reduced from chlorine contents by Knudsen's formula.)

Station	Tide	*June	*July	August	September	October	November
Rio Vista	Low	....	22 to 35	49 to 240	50 to 160	18 to 26	.
	High			49 to 380	105 to 430	29 to 137	.. .
Collinsville	Low	5 to 20	18 to 525	650 to 1220	875 to 1345	35 to 560	9 to 85
	High			825 to 1445	1210 to 1560	208 to 1058	9 to 260
S. F.-S. R. R. O. A. & E. R. R. Ferry, Suisun Bay	Low	10 to 130	55 to 930	1045 to 1285	1310 to 1700	335 to 1300	9 to 312
	High			1060 to 1590	1670 to 1800	613 to 1470	9 to 619
Antioch	Low	....	17 to 640	275 to 865	780 to 975	70 to 589	29 to 109
	High			665 to 1350	1040 to 1390	123 to 1058	29 to 114

***Note:** No information is available as to the stage of the tide at which the samples of water for salinity tests were taken preceding July 20th.

circulation of water around Sherman Island, thereby expediting the up-river advance of the bay water.

The data in table 3 relating to the salinity of the upper bay and river waters are derived from public records collected and compiled by the State Water Commission.

SUMMARY

It appears from the foregoing that there are a number of factors to be considered in any discussion of the salinity of the upper bay and lower river waters, particularly when conditions in any year are to be compared with those in another, and, too, when any forecast is attempted as to future conditions.

Principal among these factors are the following:

1. The seasonal water output of the Sacramento and San Joaquin Rivers, and

the occurrence in sequence of years with normal run-off conditions.

2. The distribution of the seasonal water output to the several months of the year.

3. The effect of human activities upon the river discharge, referring particularly to:

a. The acceleration of the flood discharge resulting from the reclamation of large areas which, under natural conditions, were subject to inundation. The

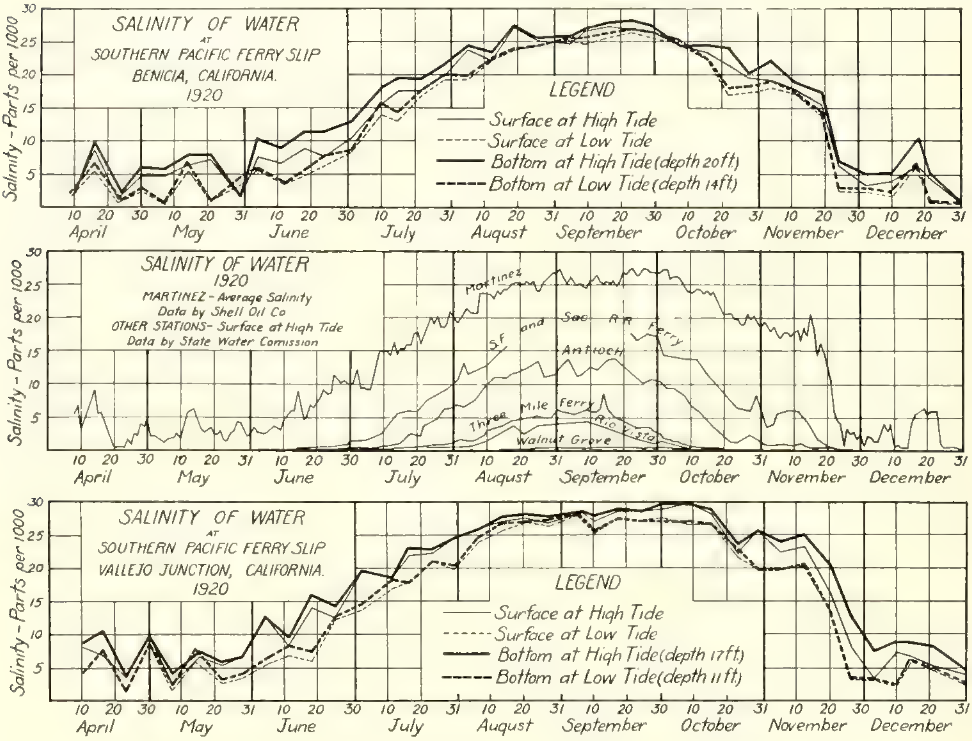

Fig. 19. Salinity of water at points in Carquinez Strait, 1920.

natural flood basins acted as retarding basins, prolonging the river's flood stages, thereby impeding and delaying the arrival of ocean water in the upper bays. The flood basin has already been materially reduced.

b. The reduction of the discharge of the rivers into Suisun Bay, notably at their low water stages, by the withdrawal of water for irrigation in the deltas of the rivers and at up-river points.

c. The regulating effect of storage reservoirs tending to augment the low water discharge of the rivers.

d. The accession of return water which, though relatively small in amount, is, nevertheless, increasing as irrigated areas are being extended. This not only affects the stream flow but also the quality of the water. The return water contains more mineral matter in solution than the natural river water.

e. The modifications of channel alignments and dimensions, resulting from work done in building levees and particularly from the work being done by the United States in cooperation with the State in the lower reaches of Sacramento River, which have a material effect upon the tidal flow in the lower reaches of the rivers.

CHAPTER IV

A SALT WATER BARRIER AS A PROPOSED REMEDIAL MEASURE

The period when the up-stream penetration of salt water into the lower Sacramento river was being augmented by so unusual a series of years with light run-off, witnessed accelerated Marine Piling Committee activity due to its serious aggravation of the damaging results of teredo invasion in the upper Bay region. At about that time the effort to combat the unfavorable condition also received powerful aid from a quite unforeseen source.

Coincidentally with the industrial development along Carquinez Strait, there had taken place the larger part of the greatly increased irrigation draft upon the waters of the Sacramento river to which reference has been made. In this irrigation development a large factor was rice growing in the Sacramento valley, while a second important factor was the reclamation and agricultural development of large areas in the delta region above Suisun Bay. The united effect of the reduced river flow and its attendant up-stream penetration of salinity was an increasing interference with the use of the river water for irrigation, as well as for industrial and domestic purposes in the lower river reaches. By 1920 this had become so serious as to prompt legal action by the owners of delta lands and waterfront property of the lower region, under the leadership of the City of Antioch, against the up-river users of water, particularly the rice growers who were consuming such great quantities of water in the late summer and fall. This case, which thus became known as the Antioch case, was tried before the courts of California in that year.

While it was shown in this case, that under natural conditions of small low-water output in such years as 1920, there would be considerable up-stream penetration of ocean water, it appeared also that the irrigation activities, by decreasing the low water flow of the rivers, particularly of the Sacramento, would contribute in some degree to the increase of salinity of the waters in the upper part of Suisun Bay, and therefore, also, to the distance up-stream to which ocean water penetrates. To this condition the delta landowners, by their large use of water on some 400,000 acres of cultivated lands in and adjacent to the delta, are, of course, themselves contributors. It was contended in the Antioch case that the owners of land along the lower reaches of the rivers were entitled, under the doctrine of riparian rights, to have the river water flow past their lands as it did originally, unimpaired in quality. Enough water, in other words, should, according to this contention, be allowed to remain in the rivers to provide a barrier against the encroaching ocean water which is brought up from the bay on each high tide at the river's low stages, and to prevent that water from getting any farther up-stream than it did under natural conditions.

To restore natural conditions it would obviously be necessary also to let the floods or freshet flows come down to the bays as they did under natural conditions, so that the waters of Suisun Bay would be kept fresh late in the season. It should be recalled in this connection that before lands were reclaimed in the Sacramento and San Joaquin Valleys there were large overflow basins in these valleys, notably in the Sacramento Valley, which were filled by the freshet waters through high water outlets from the rivers or by overbank flow; and the discharge from these basins into the lower reaches of the rivers continued long after the river would have fallen to a low stage if these

basins had not acted as retarding basins. By cutting down the peak discharge of the rivers these basins also prolonged the rivers' high stages. They thereby became a material factor in keeping down the salinity of Suisun Bay and, therefore, too, in keeping ocean water out of the delta channels. It is obvious that natural conditions, antecedent to the abandonment of these basins (now mostly reclaimed to inundation) will never be restored, even though the lower delta land owners would benefit thereby. It is perhaps not so obvious, but nevertheless true, that a finding by the courts in favor of either group of parties to the controversy would be an unsatisfactory outcome. It should be settled in some other fashion.

The desire to find a remedy for the condition complained of by the delta landowners, as well as by the owners of water front property along the shores of the upper bays and the strait of Carquinez, to find means of reducing the height of the flood water plane of the delta streams and to secure an abundant supply of fresh water in the whole upper bay region, has prompted the suggestion that an artificial salt water barrier be provided at the most suitable locality.

The idea that benefit could be obtained from a structure which would freely pass the freshet flow of the rivers, yet at their low stages completely check the flood tide, is not new. Studies were made as early as 1880 in the State Engineering Department of California, by the writer, to ascertain whether or not the flood water plane of Suisun Bay and at the mouths of the rivers could be lowered by means of such a structure in the Strait of Carquinez. It was found that because of the limited storage capacity in Suisun Bay this could not be done, that any barrier erected there would raise the flood plane instead of lowering it. This circumstance should be considered as absolutely condemning the strait as a site for a barrier. It may be of interest to note that the inquiry made in 1880 elicited the information from a number of the older pilots on the Sacramento and San Joaquin Rivers that, during the great flood of January and February, 1862, there were three weeks during which there was no reversal of tidal flow in the strait. At that time there had been no reclamation of overflowed lands; there was a great sea of water covering the entire delta area and adjacent lands.

The recent renewal of the suggestion that relief from the evils of salt water in the upper bays and in the river delta region could best be had through the aid of a barrier has prompted the authorization of a study of this problem by the Department of the Interior under financial assistance by the State of California and by private parties. It is understood that structures have been designed, with considerable attention to detail, for sites both on the Strait of Carquinez and at the narrowest point below San Pablo Bay. These are to be followed it is hoped with adequate study of the economic aspects of the problem.

In general, the desirable location of such a barrier is as far down-stream as possible, in order to bring the resulting benefits to the greatest possible area and to the greatest number of people. Several sites are being studied as to their relative advantages and disadvantages. Of these the one farthest down-stream is at the Narrows, below San Pablo Bay. The discussion of benefits will be restricted in this paper to a barrier at this point only. It will suffice to say with reference to any location farther up-stream that such alternative location would confer only a restricted benefit and would have the disadvantage of raising the flood plane in the delta region of the two rivers. This, as already stated, is a matter of such vital concern that, if it had been given its deserved serious consideration, this would undoubtedly have definitely eliminated any such project.

It will be seen that such a barrier will automatically eliminate teredo and teredo troubles from the area, which will become a fresh water one, above it. This, in view of

the damage, amounting to more than $25,000,000 already caused by this borer in the upper Bay and straits region, is a matter of some significance. And the largely increased area over which this protection will be effective with the lower barrier site, as against one higher up, adds additional weight to the argument for that site.

A properly located, properly designed salt water barrier at the Narrows, below San Pablo Bay, will convert both San Pablo and Suisun Bays into fresh water bodies with a combined surface extent of about 110,000 acres. The Sacramento and San Joaquin Rivers will annually discharge into these bays enough water to replace their water contents from two to over ten times, so that they can be depended upon to furnish the water that will enable these modified bays to be used as a reservoir of fresh water. The barrier, it may be assumed, will be so arranged that in winter the flood flow of the streams can find passage through automatic flood gates. These might be arranged to operate on a concrete sill placed below the Narrows where it is 3 to 4 miles wide, and should have a capacity such that piers between openings will obstruct the flowing water to the extent of only 2 to 3 inches. In addition to the flood gates there should be a second set of gates, preferably at the upper edge of the concrete sill, provided with power control. These gates would then be used to hold the summer water above the barrier (that is, in the two bays) at about present ordinary fall high tide elevation, thereby effecting the proposed conversion of these bays into a great fresh water reservoir. The annually available contents of this reservoir, from an ordinary high stage about 6 feet above low tide down to say one foot above low water, will be about 500,000 acre feet. This amount is, however, not all the water that can annually be drawn from this reservoir, because to this amount should be added whatever the rivers are discharging, less, of course, a small amount required for lockages at the barrier. Moreover, the reservoir will be full every year about July 1st and it is only the late summer and fall demand of the irrigator which will deplete its contents. Such a supply, conveniently tapped from the banks of any of the channels, natural or artificial, in the delta region of the San Joaquin and Sacramento Rivers will adequately meet the requirements of more than 300,000 acres of delta lands under intense cultivation as well as the needs of more than 100,000 acres of mainland bordering on the delta. Furthermore, the sloughs extending from the bays into the salt marshes would be permanently filled with fresh water, affording an abundant supply with which to freshen the land and make it available for farming.

The reservoir created by the barrier can be so regulated as to surface elevation that during the summer and fall there will always be from one to five feet more water in the bays and in the lower rivers—up to Sacramento and up to Stockton—than now obtains at the rivers' low tide stages. In the reservoir there will be only a one-way current and this current will be sluggish except when the rivers are at high stages. Navigation will, therefore, get some benefit both as to depth of navigable water and elimination of uncertain bay currents.

There will be no more nor less silt brought down into the bays then than is now brought down by the rivers. This silt moves at flood stages. Under present conditions it meets the checking influence of the up-stream current at flood tide, it is dropped at slack water, and its deposit is encouraged by the admixture of ocean water which acts in some measure as a precipitating agent. The probability is that rather less than more silt will remain in the two bays, if converted into fresh water lakes, than at present.

The salt water barrier, if placed below San Pablo Bay, will, as already intimated, assist in keeping down the elevation of the flood planes of the two upper bays and of the lower rivers. This results from the large reservoir capacity above the barrier. During the high stages of the rivers, which occur in winter and in early spring, the

flood gates will be set to let water pass out of the reservoir. At each ebb flow in San Francisco Bay the water in San Pablo and Suisun Bays will then run out until these lakes are down to their present winter low tide levels. As the tide in San Francisco Bay, thereupon, begins to rise the gates will close automatically. On their down-stream side the tide may rise to an extreme high stage while on their up-stream side the reservoir is rising under the influence of the river discharge. As this discharge is not great enough to bring the water in the two bays fully up to high tide before the tide in San Francisco Bay begins to ebb again, the reservoir feature of the project will, as stated, lower the flood plane of the bays and of the entire delta region.

The fresh water in such a reservoir as described will be available for domestic and industrial use. It can be made potable by filtration and chlorination, as is done everywhere throughout the United States where water from an unpolluted source is not available at a reasonable cost. This would solve the water supply difficulties of the towns on both sides of the bays and along the strait of Carquinez and would result in a tremendous industrial development.

The barrier itself if located, for example, on a fairly direct line from Richmond toward San Rafael, would be ideally located to support a highway and a railroad bridge, thus connecting the northerly coast counties with the East Bay population center.

But where there are so many and such vast benefits there must be some disadvantages. Of these the first to be noted is the inconvenience to ships that navigate the upper bays and river waters, which would be delayed somewhat at the barrier where they would have to pass through locks. There is an ordinary rise and fall of tides in San Francisco Bay of about five feet. The extreme range of tides is 10 feet. At the barrier the water will, according to the stage of the tide, sometimes be higher on its up-stream side, and sometimes on its down-stream side. Or, again, the water elevation on both sides of the barrier may be, though perhaps only momentarily, at the same level. Because the passing of vessels through locks involves a delay, they are an inconvenience to navigation. But this objection holds equally for a barrier at any location and, in this case, as already pointed out, there is an offsetting advantage in better navigation above the barrier, which will be effective over a wider area than in the case of a barrier farther up the Bay.

It has been suggested that in case of war there must be no obstruction between the main bay of San Francisco and Mare Island. To meet this requirement, if emergency arises, the use of the bays as a fresh water reservoir can be temporarily abandoned. All gates will then be kept wide open for a few hours or even for a few days and ships can pass through the lock chambers unobstructed without having to wait for any filling or emptying thereof.

It is to be noted, too, as affecting San Francisco Bay that such a barrier would cut off from the area of the bay now affected by the tides one-third or a little more. The volume of the water which goes in and out through the Golden Gate on flood and ebb tides would be correspondingly reduced. There would be less velocity of current, with some benefit to navigation and there might be some effect in the course of time on conditions within the influence of these Golden Gate currents. It may be argued that the reduced flow of water over the bar outside of the entrance to San Francisco Bay will have the effect of raising the crest of the bar. This is highly improbable. It need not be feared. Furthermore an artificial channel across the bar 2000 feet wide and 40 feet deep at lower low tide has just been completed by dredging. This channel will have to be maintained by further dredging whether or not the in-and-out flow of water through the Golden Gate be modified by the propcsed barrier.

Where damage to private property will occur is not apparent, except in the taking of a few acres of land for rights-of-way. It is rare indeed to find a project which will confer such varied and general benefits.

But the benefits described cannot be had without some expense. There is no difficulty in the way of building the barrier which cannot be readily overcome. The head of water against the barrier when it acts as a dam will never exceed 10 feet; rock foundation is not required. But the water is deep and the structure will be long. Its cost should preliminarily be taken into account at $30,000,000 to $50,000,000. This is relatively small compared with the benefits, direct and indirect, which its construction will bring. It is a project deserving of the most careful examination. Above all it will be necessary to determine what agency shall be created to construct and operate the barrier, and to agree upon a plan of apportioning its cost to the United States, to the State, to the Municipalities which will be placed within convenient reach of abundant water supplies, to the owners of tide marsh lands, to the delta landowners, to the railroads which will utilize the structure as a bridge and to the many private industries which will have a share in the resulting benefits. It may in fact be necessary to provide for the organization of a district, so as to create proper facilities for evaluating the relative benefits as a basis for the assessment of cost of the structure to those who are benefited thereby.

It should for the present be assumed that, where the resulting advantages are of the magnitude above indicated, sooner or later means will be found for the erection of a properly located and properly designed salt water barrier.

ENGINEERING SECTION

By R. M. Neily *and* W. H. Kirkbride
with special collaboration from
F. D. Mattos, H. E. Squire *and* C. L. Hill

CHAPTER V

THE ENGINEER'S RESPONSIBILITY IN MARINE STRUCTURAL PROBLEMS

It is likely that no type of structure is subjected to such severe and adverse conditions as that serving in sea water. The superstructure involves all the problems of those built on land, and the substructure, in addition to being constructed on a complex and uncertain foundation, must be capable of resisting the action of tidal currents, waves and storms, impact of ships, abrasion of floating objects, severe weathering action, chemical action of sea water and, in the case of timber substructures, the ravages of marine borers. These structures constitute a most necessary and vital element of industry and commerce; they involve the expenditure of great sums of money; they are expensive to maintain; and, when once established, their deterioration is extremely serious, not only because of the direct cost involved but because of the interruption of operation when repairs and replacements are necessary. The obscured and uncertain condition of the substructure presents many obstacles to design, construction and maintenance; it sometimes results in sudden failure of the structure, entailing a loss of life and property which could have been avoided had the condition been known.

The average organization financing a new project demands that type of construction which gives the desired facility at the lowest first cost. In the case of marine structures a lowest first cost usually involves untreated timber piling. The facts that other structures in the vicinity have been built with such substructure material and with apparent success, that no borer attack may have been observed, or that the attack may seem to have been negligible, are by no means sufficient warrant for the conclusion often drawn from them that the borers can be disregarded and that unprotected timber is adequate. It has been amply demonstrated that absence of borers in the past is no assurance of their continued absence. They are sufficiently distributed along all sea coasts to appear anywhere and some of them can exist in salinities as low as 5 parts in 1,000; sporadic infestations often occur in regions previously unmolested; conditions of salinity sometimes change, as for example in river estuaries, increase of salinity bringing with it borers; and it is known that substructures of untreated timber can be destroyed in a few months, the attack being often unnoticed until actual collapse occurs. *Teredo navalis* settling in the breeding season of July and August has in fact caused the destruction of unprotected piling by the end of October.

Under these conditions it is obvious that a critical responsibility rests with the engineer. Where borer infestation is possible and timber is involved, an understanding is required not only of substructure practices but of essential facts respecting the methods of attack, habits, breeding, and life history of the borers themselves. If a new project is contemplated, the limited life of untreated timber in that location must be demonstrated and proper protections or substitutes recommended; if the structure of unprotected timber exists, means must be instituted to note carefully the advent of

borers or the degree of their attack. The arrival of a heavy infestation does not permit delayed research or temporizing; command of a practical knowledge of the subject is required so that in the case of a large project the matter can be placed before those in executive control in time to permit authorization of necessary expenditures and execution of protective measures.

While the research work of this Committee has centered essentially about borer attack on timber, it has necessarily given consideration to the general subject of marine piling materials, including materials other than timber and which are ordinarily, if not always, immune from borer attack. The availability of timber, its natural adaptability as piling, its comparatively low cost and ease of handling, cause it to rank foremost as a piling material for general use. The borers achieve prime importance because they obstruct the use of this most plentiful and available natural piling material, and not because they constitute a greater problem than any other adverse conditions. An effort has been made to ascertain the comparative advantages of the various piling materials and to indicate the adaptability of each to specific conditions. Thus the solution of the problem has been sought in a broad way, considering borer attack as one of many destructive influences to be resisted by utilizing all available means.

The general study has demonstrated that more than one solution of the problem may be practicable, and that the degree of success obtained in specific cases depends primarily upon the degree of understanding of the factors involved. If any of the numerous adverse influences operating on a structure are neglected, the best of materials may be prematurely destroyed. Materials are available capable of giving an economic life suitable to almost any combination of conditions; the problem is one of finding the proper way in which to use those materials. It is not improbable that successful use can be made of many of the practices developed during the past but confidence in which has been shaken by the occurrence of failures. Such failures have sometimes resulted in cases where great effort and elaborate methods were applied, and failure was interpreted as indicating that the entire principle involved was wrong; yet it is commonly found that premature failures are traceable to neglected or improper details. While recognizing the possibility of great advance in knowledge in the future, we have surely reached the point, therefore, where we may profit by the past experiments in which we have clear evidence that methods are as critical as mediums and that economy or loss will result according as proper measures are adopted or neglected for both methods and mediums.

In the function of the engineer to create structures with the greatest economy, he is constantly in search of more efficient practices, and has frequent recourse to experiment and test. It is therefore important that he know of those principles which have proved unsuccessful, as well as of those which have proved successful. Schemes are constantly appearing under new names involving only old ideas long since found worthless. The Committee has believed that it can render best service, not so much by exploiting new timber preservatives or substitutes, as by developing the principles controlling the successful use of all methods.

CHAPTER VI

MARINE CONDITIONS AS AFFECTING MARINE CONSTRUCTION

Exposure

Marine structural problems are largely conditioned by the nature of exposure, which may range from that of the highly protected harbor to that without protection from the violence of the ocean. While the structural requirements may be identical with regard to loading, depth of water, or condition of substrata foundation, differing exposures will require different procedures. All adverse conditions are accentuated in ocean exposures, both by the chemical effects of sea water and by the destructive impact forces of waves. A method of timber pile protection which may serve perfectly in calm water may be worthless in locations subject to severe wave action. In general, ocean exposure will require extreme precautions, with the elimination of details incapable of withstanding severe conditions. The various destructive influences and the manner of their effect on various materials are discussed in the following pages.

Influences Operative at Various Substructure Levels

Substructure materials are subjected to a series of influences at different levels which may be designated, from top to bottom, as the "air," "air-water," "water" and "mud" sections. The "air" section is that above high water; the "air-water" section is that alternately exposed to air and water either from wave action or from tidal or seasonal changes in water level; the "water" section is that constantly submerged in water; the "mud" section is that below the mud line. A single unit which passes through these four levels must be designed to fit conditions prevailing in each, which may be briefly outlined as follows:

Air..........Connecting to superstructure
Bracing
Loading stresses
Decay of timber
Corrosion of metal
Abrasion of boats
Fire hazard

Air-Water....Loading stresses
Current stresses
Impact of waves
Effect of temperature changes
Abrasion of boats and floating objects
Corrosion of metal
Decay of timber to mean tide level
Leaching action of water on chemical preservatives
Action of salt water
Marine borer attack on timber, especially that of *Limnoria*

Water.......Loading stresses
Current stresses
Impact of waves
Bending stress in flexible piles

Abrasion of boats and floating objects
Leaching action of water on chemical preservatives
Action of salt water
Marine borer attack on timber
Shell fish and mollusks

Mud.........Loading stresses
Bending stress in flexible piles near top of substrata
Bearing on substrata
Side bearing of substrata—mud, sand, rip-rap, etc.
Frictional connection with substrata for piles
Marine borer attack on timber near top of substrata

Of these four levels, the air and mud sections present conditions essentially similar to those of land structures. The greatest problems prevail in the two intermediate water sections. Among numerous adverse influences, the air-water section is characterized by the severe weathering and other deteriorating actions common to conditions where materials are exposed to both water and air, particularly the decay of timber, its attack by the borer *Limnoria*, when that is present, and the corrosion of metal, such as reinforcing steel in concrete. The water section is characterized especially by borer attack on timber. Metal corrosion, due to the action of sea water, is only less active than in exposure to alternate air and water. Thus if the two most common substructure materials be considered—timber and reinforced concrete—the water section is most critical for the former, and the air-water section for the latter.

Changes in Water Level

Alternate wetting and drying of a substructure material may be caused by wave spray, or by tidal or seasonal changes in water level. The most adverse condition is that created in ocean exposures by the combination of wave spray and tidal change, which may involve a considerable height of the structure; in protected harbors the tidal change and the wave wash will usually extend over only a few feet. In rivers the seasonal change of level may be as much as 30 or 40 feet, although usually it is much less. While this last case gives a large range, the weathering and corrosive effect is reduced because the change is seasonal and because the corrosive effect of fresh water is less than that of salt water. Under usual conditions, the maximum height of substructure subjected to alternate wetting and drying is that from the lowest water level to the wharf floor: at San Francisco, where the tidal range is from 5 to 8 feet, wharf floors are built 14 or 15 feet above low water; at Sacramento, on the Sacramento River, the annual change in water level may be as much as 31 feet and wharf floors are about 36 feet above the low level. Thus the height of substructures to be protected against the adverse conditions of the air-water section in the San Francisco Bay region and its tributary rivers, is from about 14 to 36 feet.

While the range of water levels is relatively stable in ocean and harbor locations, new conditions are often created in rivers and their estuaries. This may be caused by years of unusual drought, by the withdrawal of large quantities of river water for irrigation or municipal purposes, by reclamation projects, by the impounding of head waters, or by locks and dams. Developments which tend to stabilize the water level near the high water elevation to which the wharves are built are desirable, whereas those which lower the level usually create both structural and operating difficulties.

The falling of the water level may facilitate inspection and repair of substructures to a certain degree, but this advantage is completely offset by the many adverse conditions resulting from change in water level. At low tide some structures may be

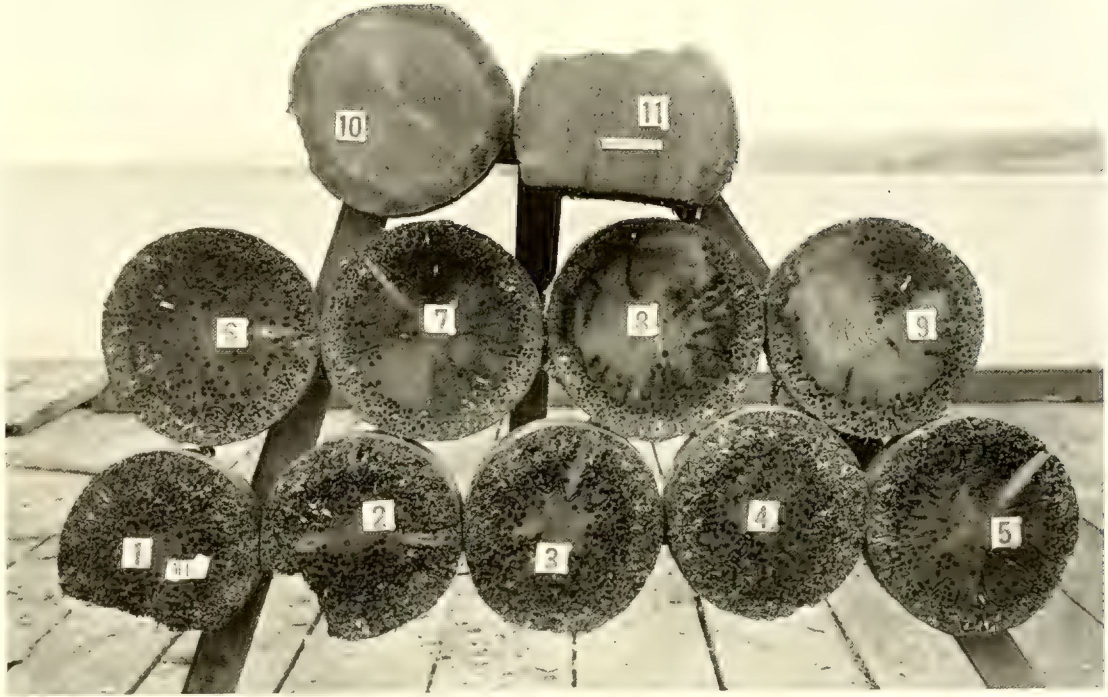

Fig. 20. Fender pile, Shell Oil Co. dock, Martinez, California. Sections three feet apart, mud line to high water. November, 1920. Note deeper penetration on down-stream (right side) and offshore (lower) exposure. (*Shell Oil Co. Photo.*)

completely exposed above the mud line and borer attack on timber involved thus be reduced. However, sufficient water usually stands on the mud surface to allow action by *Limnoria*, so that it can destroy such material. While protections can be carefully placed and maintained under such conditions, the advantage applies only to a comparatively limited proportion of construction; in a majority of cases there must be a sufficient depth of water at low tide to permit boat operations.

In general, the most adverse condition is that of sea water having wide changes in level occurring with greatest frequency. Adverse factors, in their bearing on the use of various types of substructure, are discussed in the following pages.

Currents

The movement of water in the form of currents creates numerous conditions having a direct bearing on sub-structure problems. Of the many forms of substructure which may be built, ranging from solid fills to piling, the latter is often required in order that the structure shall offer the least obstruction to currents. In tidal harbors the tidal prism, or the volume of water between tidal levels, must not be decreased. Government rulings establish the "bulkhead" line, beyond which no solid embankment can be built, and the "pierhead" line, beyond which no structure can be built; wharves built between these two limits must be supported on piling. Thus, while it is often physically possible to replace pile foundations with solid fills and eliminate the problems of maintaining the piling, this can never be done in the case of structures outside Government bulkhead lines. Pile structures will always be required where conditions demand that current action shall have minimum obstruction.

San Francisco Bay furnishes a striking example of tidal conditions with strong currents prevailing. As explained in the Hydrographic section, this bay, over 50 miles long and averaging several miles in width, is connected to the ocean by the Golden Gate channel, less than a mile wide and over 300 feet deep at the center. The volume of tidal water passing through the Gate is estimated to be over 2,000,000 acre feet. The current created by this immense flow is extremely strong, particularly along the shores adjacent to the Gate channel, on the south side of which the San Francisco waterfront is located.

In 1886 it was reported by the Board of State Harbor Commissioners that marine borer attack was more severe in the northern portion of the waterfront adjacent to the Gate channel, where the current is stronger than elsewhere. This condition has prevailed to the present time and, coupled with other similar observations, has led to the general conclusion that marine borer attack is greater in strong currents than in water of slight movement. In a similar way it has been found that in a single pile the attack is greatest on the side most exposed to the current. On the east shores of the Bay the current action is much less than at San Francisco, which doubtlessly accounts in part for the reduced borer attack there.

Prevailing currents influence general waterfront plans. In the Historical section mention is made of the trouble experienced with the original San Francisco waterfront line as established by the State Legislature in 1851, this line following an irregular, saw-toothed course along the rectangular city streets. Structures conforming to it projected in various directions and interfered with the tidal flow by creating eddying currents, which caused shoaling of wharf slips and required constant dredging. The change in waterfront line and plans in 1878 was made so that the line might follow the prevailing currents in a smooth curve and that the wharves would offer least obstruction to the current, thus eliminating the eddying effect.

The direction or orientation of wharves and ferry slips must often take into

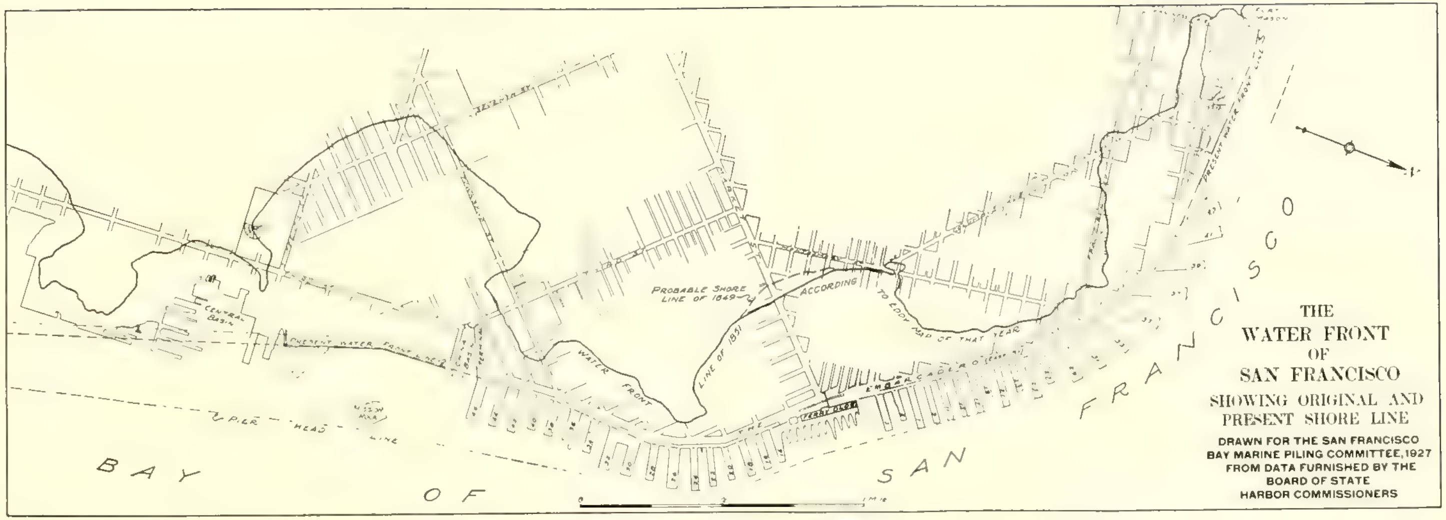

Fig. 21. Map of San Francisco waterfront showing original and present shore lines.

account the effect of current on the movement of boats, since the design of the structures must provide for the impact of boats, either while they are docking or are moored in the path of the currents. In ferry slips the combination of current action on the boats and their inertia, under the necessity for speedy operation in and out of the slips, requires a very strong and flexible structure to withstand the shocks without damaging either the boats or the slips.

Current action also accelerates leaching of chemical preservatives, either those used for timber protection or as paints for metal protection. This partially accounts for the shorter life of such protections in water of strong current than in water of less movement.

Influences which increase current velocity, or propeller action which agitates the water, will tend to cause cutting and scouring of the mud bottom. While this may be desirable, at least to the extent of preventing filling, and where adequate provision has been made for it in substructures, active scouring has often proved disastrous where timber piles have been protected only above the original mud line with the protection not carried down far enough to allow for the scouring. In such cases the unprotected timber becomes exposed to borer attack and is destroyed. Scouring will also in general tend to decrease the stability of structures unless they are carried down an adequate distance below the mud line.

The foregoing indicates that the most adverse condition is that where strong currents prevail.

Salinity

The condition of salinity may range from the negligible amounts in fresh river water to ocean salinities of from 30 to 35 parts salt in 1,000. This saline content serves to accentuate many adverse marine influences. The rate of corrosion of metal is greater in salt water than in fresh, which thus accelerates the deterioration in salt water of cast iron, wrought iron and steel piling, sheet metal coverings for timber piles and reinforcing steel in concrete. Iron and steel piling can be protected to a certain extent by painting, but this eventually fails unless renewed. Yellow metal covering for timber piles has been found impracticable because of corrosion; copper has given good service, but must be thick enough to withstand a certain amount of surface corrosion. Many failures of reinforced concrete have been caused by rusting of the reinforcing steel, and protection against this corrosion constitutes one of the greatest problems in respect to this type of material. Concrete work is likewise adversely affected by salt water because of chemical action with the ingredients and the formation of laitance.

Salinity is particularly important where marine borers are concerned. The danger point is about 15 parts salt in 1,000. If this salinity, or greater, can occur and borers are present, their attack on unprotected timber can be expected. As explained in the Biological section, *Teredo navalis* is particularly destructive in the lower salinities, from 10 to 20 parts in 1,000, a condition to be found in river estuaries. River discharge may vary so that the salinity is reduced below 15 in 1,000 for a period of time, but if it rises again to this amount during the breeding season of *Teredo* and so remains for a few succeeding months, unprotected timber will be destroyed. This borer will survive in nearly fresh water if a salinity of 5 parts in 1,000 occurs every 30 days or oftener (See p. 261). *Limnoria* and *Bankia* seem to require higher salinities, 20 parts in 1,000 or more (See pp. 292 and 327). Hence all borers are found active in water of 20 parts or more of salt in 1,000.

Particular jeopardy is involved in river estuaries where fresh water conditions have led to the use of unprotected timber in wharves, and where an unusual reduction

of river flow may allow salt water to enter, bringing with it the marine borers. This development is illustrated by the destruction which occurred in the Carquinez Strait territory in recent years. The reduction in river flow, which permits the increase in salinity, may result from many influences, such as unusually low rainfall or reduced rainfall in mountain sources of streams, new irrigation projects, diversion of streams for industrial or municipal supplies, or storage reservoirs.

Since salinity may bring with it borer attack, as well as other adverse conditions, it is important that means be established to give information respecting salinity conditions where timber is used under such fluctuating conditions. In many cases salinity records are kept by industries located in the vicinity. Such records should be carefully observed to ascertain or predict developments. The technique of salinity determination, while exacting, is relatively simple and not beyond the reach of any one with the most elementary chemical knowledge. Salinity records should by all means be supplemented by systematic use of test pieces for determining occurrence, character, intensity, and progress of borer attack. Where borer attack is not clearly impossible, it is in the highest degree prudent as well as profitable to use every possible means to foresee a dangerous condition in time to adopt protective measures.

As time goes on, interior development will tend to alter river flow, in the majority of cases reducing it. In some instances the river flow is increased, as for example where flood control channels are being built to carry off flood waters which now inundate agricultural lands; but while this will temporarily increase the run-off reaching the rivers, it is likely to be offset by the influences tending toward decrease. In a few cases locks or dams may be built permanently shutting out sea water. In general, however, it is likely that ocean water will steadily advance into the estuaries of rivers accessible to it.

Infestation

The prevailing condition of borer infestation is usually a well established fact—the borers are known to be either present or absent, and protective measures are either adopted or disregarded. Perhaps the most dangerous situation is the beginning of borer attack in a region previously without it. An infestation is in reality contingent upon two general factors: marine conditions and the presence of timber which can be attacked. The former will control the intensity of infestation, the latter will provide a breeding ground in which it may be established and continued.

An infestation may be conveyed from one locality to another either by some such agency as driftwood or log-booms, or by water currents which carry the borer larvae. If unprotected timber exists in a locality reached by such agencies it will eventually be attacked and the infestation established; if no such timber exists, the larvae will soon perish and any borers in driftwood will die off as soon as the wood is destroyed. A locality near an infestation may remain comparatively free from borers if conveying agencies are absent. A structure may even be built of unprotected timber, in an isolated location, where conditions are suitable for borer life and within a few miles of an infested region, and may remain unmolested or only lightly attacked for some time. The possibilities of a continuance of such immunity are increasingly unlikely, for some chance circumstance is almost certain to bring the borers; and as time goes on other structures are likely to be built in the vicinity, giving a greater amount of exposed timber and increasing the possibility of establishing infestation. Under such conditions the rapidity with which the borers breed will soon make the attack as severe as elsewhere.

The apparent absence of borers in a locality relatively near an infested region has often led to the mistaken conclusion that prevailing conditions unfavorable to

borer life would continue to repel them, not taking into account the fact that such conditions often change.

FACTORS CONTROLLING INFESTATION

The most important marine conditions which control infestation are salinity and current action (which have been previously discussed under separate headings), relative purity of water, depth of water and temperature. In a harbor such as San Francisco Bay all degrees of these conditions are found, low and high salinity, slow and rapid currents, pure and contaminated water, shallow and deep water and a moderate range of temperature. Hence many variations exist in degree and character of borer attack.

RELATIVE PURITY OF WATER

It has been observed that borer action is greatest in uncontaminated sea water and that it has sometimes been reduced or even prevented by local contamination, such as sewage or factory waste. Such a condition has often led to the conclusion that no borers were present or that no protection against them was necessary, and structures have been built accordingly. But such contamination may disappear; different kinds of pollution may be differently effective; and different kinds of borers may be differently affected by the same contamination.

The first condition is illustrated by the experience of the Howard Company of Oakland who built a pier of untreated piling in Oakland harbor in 1900. The untreated material proved so satisfactory that subsequent replacements were made with it. It happened, however, that their structure was being protected by effluent from a gas plant which was being discharged into the water nearby, depositing a surface coating on the piles. This practice was later ordered stopped by the Fish and Game Commission in cooperation with the Oakland Port authorities. With the elimination of the effluent the water became similar to that prevailing elsewhere and borer attack began. As a result it was soon necessary to replace the piling with protected material.

The degree of protection afforded by sewage has probably been overestimated. During this investigation *Bankia* and *Limnoria* have been found under conditions of considerable sewage pollution (see p. 267), while *Teredo* has been found in timbers close to the mouths of sewers.

In harbors such as San Diego, where large amounts of crude oil are constantly being shipped, the spilling of oil coats the piles between tide levels and temporarily protects them in this section.

DEPTH OF WATER

It has been found that borer action is greater in deep than in shallow water. A majority of wharves and piers are built so that they project from the shore in shallow water to deeper water at the outer end. In such a case shipworm attack is greatest towards the mud line in the deepest water (see p. 292 and figs. 3 and 20), while structures built completely in shallow water are usually attacked only lightly by shipworms. But limnoria is not thus deterred; his attack is indeed greatest between tide levels, although extending to considerable depths below that zone.

TEMPERATURE

Borers are known to attack timber in all latitudes. In general their activity increases with the water temperature, although certain species, such as *Bankia setacea*, are adapted to northern waters and thrive best under relatively low temperatures

(See p. 292). The intensity of attack in higher temperatures may be accounted for in part by the facts that propagation and activity of the borers is increased in the warmer waters, and that such water tends to leach out chemical preservatives more quickly than does the colder, hence destroys the effectiveness of preservatives sooner.

TESTS AND OBSERVATIONS OF INFESTATION

If information on actual conditions of infestation in any locality is lacking, tests should be conducted to determine the condition. They must be made with care,

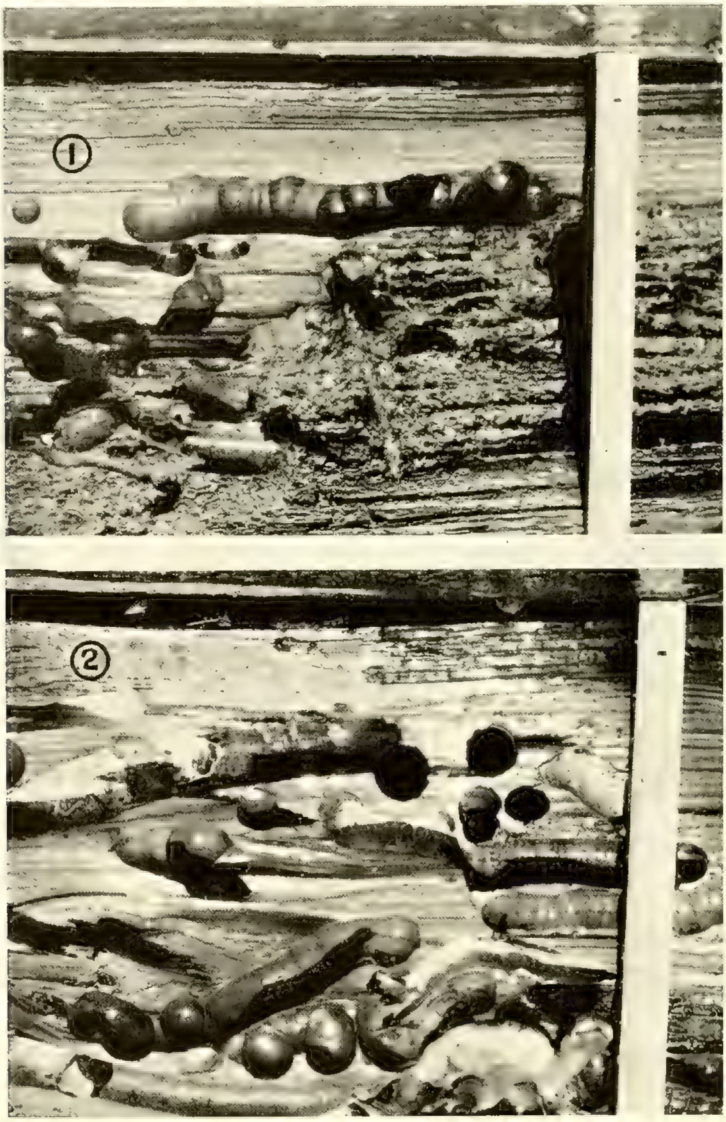

Fig. 22. (1) Creosoted Douglas fir pile from Pier 7, San Francisco, destroyed near the mud line by *Bankia* and *Limnoria*. Note deviating direction of *Bankia* burrows.
(2) The same, *Bankia* burrows, only, within creosoted zone.

bearing in mind all the influences to be considered, as previously discussed; and it must be understood that the results thus obtained will show only conditions prevailing

at the time of the experiment. Whether the condition disclosed will continue or not is another matter and must be judged by consideration of other controlling factors and by repeated tests.

The first information to be secured is that on salinity. If it is found, either by actual test or by reference to existing records, that the salinity is sufficient for borer activity, then test timbers can be exposed to determine their presence and the intensity of attack. The information usually desired in connection with piling material is the practicability or impracticability of unprotected timber, the life to be expected from it, or the extent to which protective measures should be adopted. Since unprotected timber will last a year or less under severe conditions, if protections are to be justified they must be capable of prolonging that life many times. It is therefore obvious that a complete test of ultimate life for a protected type of wood construction is impracticable because of the time required. For this reason the intensity of attack is measured by the effect on unprotected wood and the probable life of protections is judged accordingly, on the basis of data for the protections concerned, such as are presented in this volume. (See p. 177.)

The test specimen must be exposed under all conditions which could normally prevail for a structure at that point. Where *Teredo* or *Bankia* are involved the specimens should be placed in the water just before their breeding seasons (see p. 190) for the reason that this is the time at which initial attack is made by them. If placed in the water after the breeding season there may be no attack until the next year, which will give a negative result until that time and, if not understood, may lead to the incorrect conclusion that borers are not present. The destruction of wood takes place during the period succeeding the breeding season, in which the borers grow to maturity; hence the specimen should remain exposed for at least several months. In the case of *Limnoria*, which in the mature form is free to move from place to place and apparently breeds throughout the year, attack may occur at any time, if that borer is present in the vicinity or may be conveyed there by driftwood or other agencies, and if salinity is suitable.

The test specimens should be exposed in the deepest water, beginning near the mud line where the shipworm attack is greatest. *Limnoria* will be more plentiful near low tide level, but are not likely to be absent at any level, if present in that location. Specimens must be prevented from rubbing against other objects because this would hinder borer attack on the abraded surface and, even though they secured a foothold, would reduce their activity below that otherwise normal under the given conditions. Instructions for the preparation and installation of test boards will be found in Appendix B.

CHAPTER VII

MARINE STRUCTURES

The following discussion considers specific problems of the design of marine substructures of simple types, such as wharves and piers, with particular reference to the use of timber as affected by marine borers, and to the use of substitutes for timber, such as reinforced concrete. While the recommended practice applies to all marine structures, no attempt is made to cover large special projects, such as bridge piers, which must by the nature of their requirements be built of materials immune to borer attack. Structural theory is considered only insofar as it affects the particular phases of the subject under discussion.

Economic Life

One of the most important phases entering into the design of general marine structures is the determination of probable economic life. The economic life of a structure is here defined as the duration of the predominant need for the facilities furnished by that structure, on that site, without essential structural alteration or replacement by a structure of different design. Substructure materials cannot be judged and selected properly unless this element is considered and understood. The actual life of a structure is apt to be neither the economic life nor the (potential) physical life, when these do not coincide, but a compromise, whose position between the two is determined by the relative weight of such factors as unrealized physical life, and replacement or reconstruction cost, against difference in service value or earning power between the old structure and one better designed to serve a changed or changing economic need. Obviously, the most desirable consummation is that economic life and physical life be as nearly coincident as possible.

A majority of the harbors in the United States for example, are in the course of development, changes are constantly taking place and will doubtless continue to take place because of new and unforeseen conditions. Even if future conditions could be foreseen it would in most cases be impossible at the present to finance and create the higher degree of development of the future. Improvement must be gradually acquired; changes must be expected to continue; and with such change there will usually be a fairly definite limit to the economic life of structures. In many European harbors, on the other hand, facilities are relatively fixed and permanent and changes are made with relative difficulty and at great expense. Permanent construction is desirable, inasmuch as it reduces maintenance; but permanency of a substructure material is not necessarily the most significant measure of its value. Construction of high physical permanence should not be used for structures of limited economic life—which justifies the use of materials having a correspondingly limited physical life.

In this connection the factor of obsolescence is of considerable importance. Both the continual improvement in ships and methods of handling cargoes by sea and the great increases in rolling loads in land transportation, which often occur within the space of a few years, as well as changes in the character and volume of commerce, unite to render obsolescent existing structures, and to require changes in general harbor facilities, where the two kinds of transportation meet. Where harbors can advantageously provide for shipping by building quays along the shore line, ships can

berth along the quay walls and warehouses can be placed on a fill behind the wall. The harbor structures are then largely independent of changes in ship lengths, they can be built of permanent materials and can usually serve indefinitely. This type is usually adopted in river harbors, such as that at New Orleans. The Carquinez Strait waterfront is largely of this type. In this type, however, the berthing capacity of the harbor is virtually limited to the length of the waterfront along its perimeter. This limitation, together with other conditions, makes the quay type impossible of application in harbors such as that of San Francisco, where this type would give insufficient berthing capacity. The pier type is then used, the piers projecting from the waterfront line usually for a distance sufficient for the berthing of the maximum length ship. In this type of harbor, changes in lengths and capacities of ships unavoidably involve obsolescence because of relatively frequent changes in pier facilities to accommodate them. The following is extracted from a report made in 1919 by Mr. Jerome Newman, then Chief Engineer of the Board of State Harbor Commissioners:

> "As evidence of the rapidity of the changes that have taken place in ocean transportation in the last few years and the constant need for new types and larger dimensions for piers, the experience of San Francisco may be adduced. Prior to 1909, the standard pier was 80 feet wide and 600 feet long; it became necessary, on account of deterioration, to replace some of the older structures and it was decided to build for future increase of traffic and to erect permanent piers of sufficient size to handle it. The new piers were 130 feet to 140 feet wide and 650 feet to 700 feet long with 200-foot to 220-foot slip spaces as against 150-foot to 200-foot slip spaces previously deemed ample. In 1912, before commencing the construction of four new concrete piers, a large number of shipping men were consulted and in accordance with their views the piers were made 200 feet wide and 800 feet long with 250-foot slips. Two or three months ago plans were prepared for a new improvement at the southerly end of the waterfront involving several piers 235 feet in width by 1000 feet in length with 300-foot slips. In other words, in ten years the demands of commerce have increased pier width by about 80 per cent, pier length by 50 per cent, and slip width by 50 per cent; the structures thought ample at the beginning of the ten year period have become inadequate but must remain in service because they are too expensive to be torn down and the new idea of size required cannot be adjusted to existing piers."

Instances of changing conditions which have limited the life of structures can be cited for every large harbor. Those which have occurred in San Francisco Bay furnish a typical example.

Chronological Outline of Development of San Francisco Harbor Influencing Economic Life of Marine Structures

Prior to 1847	Harbor undeveloped.
1847	First waterfront line established. Waterfront property sold to public.
1849	Construction of first wharves and reclamation of waterfront property started.
1849-1869	Freight transportation almost exclusively by ship.

1851 . . . . First government act establishing waterfront limits and regulating construction of wharves. (Wharves could be built only beyond waterfront line on extensions of city streets and for a distance not to exceed 200 yards. This caused the majority of original wharves built beyond this line to be 80 by 600 feet, which remained standard until about 1909.)

1867 . . . . First seawall started, cutting off area of many original wharves.

1869 . . . . Completion of transcontinental railroad introduced competition with shipping interests.

1878 . . . . New waterfront line established by action superseding act of 1851.

1878-1890 . . . . Final seawall built along north section of waterfront cutting off original wharves and causing abandonment of first seawall. Old pier abandoned and new piers built to conform with new line.

1904-1922 . . . . Seawall built along south section of waterfront cutting off original wharves. Old piers abandoned and new piers built to conform.

1909 . . . . Size of new piers increased to 130-140 by 650-700 feet; slips 200-220 feet wide.

1910 . . . . Development of vehicular traffic, rapidly increasing, required special ferry service, particularly for automobiles.

1912 . . . . Size of new piers increased to 200 by 800 feet; slips 250 feet wide.

1914 . . . . Panama Canal completed, introducing increased shipping competition with railroads.

1919 . . . . Size of new piers increased to 235 by 1000 feet; slips 300 feet wide.

1923 . . . . Construction of transbay vehicular bridges started.

The following tabulation gives the approximate economic life of various San Francisco wharves, as represented by the actual life, from the time when they were first operated until operation stopped and they were removed, the limitation of life having been occasioned by some of the conditions cited above. It should be borne in mind, as emphasized in the preceding discussion, that the actual life of a structure in most cases does not coincide with the true economic life, due to influence of the (potential) physical life. Short lived construction materials may, of course, make the actual life shorter than the potential economic life; but in such cases structures are usually renewed by repair or rebuilding. As a usual thing the actual life is carried beyond the true economic life by a residual physical life, when the two do not coincide. In respect to most of the structures listed below, however, such exaggeration of the economic life is not believed to be serious, since during that period and in the structures listed the use of construction capable of a physical life greatly in excess of current economic life was extremely limited. It will also be understood that the life indicated is not necessarily that of the original construction, the majority of the structures having been renewed or rebuilt to a varying extent during their total life.

TABLE 4

ECONOMIC LIFE OF VARIOUS SAN FRANCISCO WHARVES
(Built and Removed to Date)

WHARF	Operated	Economic Life
Commercial St. ("Long" or "Central" wharf)	1849 to 1876	27 years
Clay St	1850 to 1876	26 years
Pacific St	1851 to 1876	25 years
Broadway	1851 to 1878	27 years
Market St	1851 to 1878	27 years
Jackson St	1853 to 1876	23 years
Washington St.—first location	1853 to 1876	23 years
Mission St. No. 1—first location	1853 to 1882	29 years
Howard St. No. 1	1865 to 1914	49 years
Pacific Mail Steamship Pier	1866 to 1907	41 years
Main St	1875 to 1910	35 years
Bryant St	1876 to 1910	34 years
Washington St. (Pier 1)—second location	1877 to 1918	41 years
Mission St. No. 2	1880 to 1914	34 years
Mission St. No. 1—second location	1883 to 1909	26 years
Steuart St	1884 to 1910	26 years
Folsom St. No. 1	1884 to 1915	31 years
Howard St. No. 3	1884 to 1915	31 years
Union St.—Fishermen's Wharves	1885 to 1900	15 years
Folsom St. No. 2	1885 to 1914	29 years
Harrison St	1888 to 1914	26 years
Fremont St	1889 to 1907	18 years
Powell St	1892 to 1907	15 years
Average economic life, 24 wharves		28 years
Minimum economic life		15 years
Maximum economic life		49 years

FERRY SLIPS	Operated	Economic Life
Original Market St. Ferry Slips	1877 to 1892	15 years
Second St. Car Ferry Slip No. 1	1885 to 1892	7 years
Lombard St. Car Ferry Slip No. 1	1891 to 1901	10 years
Second St. Car Ferry Slip No. 2	1892 to 1905	13 years
Lombard St. Car Ferry Slip No. 2	1894 to 1901	7 years
Main St. Car Ferry Slip	1900 to 1910	10 years
Lombard St. Car Ferry Slips Nos. 1 and 2—new location	1901 to 1915	14 years
Average economic life, 10 slips		12 years

TABLE 5

ECONOMIC LIFE OF EXISTING SAN FRANCISCO WHARVES (TO 1925)

A (Structures serving in original locations, having been completely rebuilt).

	First Operated	Last Rebuilt	Total Economic Life to Date
Pier 5, Pacific St.	1876	1896	49 years
Pier 3, Jackson St.	1877	1918	48 years
Pier 7, Broadway St.	1878	1903	47 years
Pier 17, Union St.	1878	1913	47 years
Pier 15, Green St.	1879	1914	46 years
Pier 11, Vallejo St.	1879	1915	46 years
Center St. Wharves	1884	(Various)	41 years
Pier 9, Broadway	1885	1903	40 years
Pier 27, Lombard St.	1888	1906	37 years
Pier 19, Union St.	1903	1914	22 years
Pier 23, Greenwich St.	1903	1914	22 years
Pier 25, Lombard St.	1903	1914	22 years
Pier 21, Filbert St.	1903	1915	22 years
Pier 44	1906	1917	19 years
Pier 42	1906	1918	19 years
Pier 46	1914	1917 (fire)	11 years
B (Structures serving in original locations, not rebuilt).			
Piers 36, 38, 40	1909		16 years
Piers 34, 54	1910		15 years
Piers 26, 28, 30, 32, 39	1913		12 years
Piers 41, 43	1914		11 years
Piers 14, 16, 18, 20, 24, 35, 37	1915		10 years
Piers 22, 29	1916		9 years
Pier 31	1918		7 years
Pier 33	1919		6 years
Average economic life to date, 39 wharves			20 years
C (Ferry Slips).			
Market St. Ferry Slips 1-7	1893		32 years
Santa Fe Car Ferry Slip	1901		24 years
Sou. Pac. Co. Car Ferry Slip	1904		21 years
Pier 36 Car Ferry Slip	1909		16 years
Market St. Ferry Slip 8	1914		11 years
Market St. Ferry Slips 9, 10	1915		10 years
Powell St. Car Ferry Slips 1, 2	1915		10 years
Average economic life to date, 15 slips			22 years

The limited life shown in table 4 illustrates a condition typical where structures are built prior to the adoption of an ultimate harbor development plan. All these structures had their economic life limited by the fact that they did not conform to new harbor plans created subsequent to their construction; hence each was removed, often while still physically serviceable, to permit rearrangement in accordance with the new condition. None of the wharves constructed prior to the establishment of the present waterfront line in 1878 exists today. The list also shows 14 wharves built

subsequent to that time which no longer exist. The period from 1878 to 1892, when the last of these 14 was built, represents the time in which the plan of harbor development was being worked out, and it is to be expected that some wharves built during this period would not conform to the final plan. It may be noted that the life of two of these structures was only 15 years, while one built in 1865 served for 49 years. This bears out the general fact that in a harbor where rapid development is taking place the economic life of wharves may have a very wide range, this life having varied in San Francisco from a comparatively few years to 50 years, with an average of about 30 years.

Wharves built of short lived piling are likely to be changed whenever the necessity arises. Since development of an industrial harbor is predicated on maximum efficiency of freight handling and transportation, all temporary facilities which hinder or obstruct such development must ultimately make way for it. As an example of this, the Fishermen's wharves listed in table 4, built of temporary construction, occupied a space which ultimately became more urgently needed for a large freight pier; hence after 15 years, when they were no longer serviceable, they were abandoned and replaced by such a pier. The new Fishermen's wharves were then built farther north, outside the area of shipping piers, where movement of the small fishing craft would not interfere with other traffic. From many standpoints this relocation was desirable, and the temporary or short lived piling used in their construction made the relocation possible without material financial loss.

Another such instance is furnished by the ferry slips listed in table 4, which had an average life of 12 years. These facilities were no less urgently needed than freight piers, but because their design required them to be built with flexible timber piling, they were of necessity shorter lived and could readily be relocated at the expiration of their life when such relocation was desired.

When physical life exceeds economic life to any large degree the money loss involved in sacrifice of unrealized physical life tends to retard destruction or replacement until the loss from inadequate service rendered by the outgrown structure equals—in many cases until it largely exceeds—the anticipated physical loss in replacement. In harbors undergoing comparatively slow development such facilities may safely have a long life. The Southern Pacific Company Oakland Long Wharf extension, 4200 feet long, built in 1869-71 of timber piling, remained in service until 1919, or about 49 years, before a change in the Government pierhead line required its removal. That the creosoted timber piling of which the structure was built was entirely adequate was shown by the fact that, at the date of its removal, much of it was pulled and redriven elsewhere; a greater investment in more permanent material would have increased the economic loss when removal became necessary. This same company is operating a ferry slip at the end of Oakland Mole—from which the long wharf extended—originally built in 1881, or 44 years ago; also car ferry slips at Benicia and Port Costa originally built in 1879, or 46 years ago, all of timber piling.

The existing San Francisco structures listed in table 5 are shown to have had an average economic life of 20 years to date, with a maximum of 49 years; all were built subsequent to establishment of the present waterfront line. By a coincidence the present structure of the Pacific Street wharf (Pier 5) which has had the longest economic life, is also the oldest now in the harbor, having been in service since 1896, or 29 years. These structures are likely to remain for many years to come, and illustrate the fact that wharves built according to an established ultimate harbor plan can be expected to have a greatly increased economic life. It is of interest to note that while the ferry slips built prior to establishment of the present harbor plan, as shown

in table 4, had an average life of only 12 years, those built subsequent to the plan, shown in table 5, have already had an average life of 22 years.

GENERAL CONCLUSIONS

The foregoing illustrates the importance of the factor of economic life. The chief general conclusion is that physical life should, as nearly as can be forecast, be equal to economic life. As to what the latter will be, it is obviously impossible to foretell the trend of waterfront development for any length of time with any degree of certainty; however, certain general conditions are likely to prevail. Waterfront locations may be divided into three classifications as follows:

A. Frontage adjoining property unsuited for future industrial or municipal development.
Structures located in such territories are likely to have unlimited economic life provided they in no way interfere with navigation. This class will include bridges and government structures such as fortifications and lighthouses.

B. Frontage adjoining property suited for future industrial or municipal development.
Structures located in such territories are likely to have a long economic life, depending on the rate of development of the territory.

C. Established municipal waterfront property.
Structures located in territories where no plan of harbor development has been adopted are likely to have an economic life of a comparatively few years; where a permanent plan has been adopted the range of life should be much greater.

Annual Cost

Information on the relative annual costs of the various kinds of piling provides a means of judging their relative merits on a fundamental basis. Establishing this annual cost, however, requires accurate data on the physical life of the types, together with all the items of expense involved throughout their complete service—and such data are difficult to obtain. The physical life of any type will vary with the quality of materials, workmanship, handling and construction practice and the prevailing conditions of use; and information on the items of expense would require records covering a long period—which are seldom, if ever, maintained because of the labor and cost involved. For this reason the elements of life and expense can only be estimated as accurately as possible from data at hand and an approximate means of comparison secured. However, the results if carefully developed should furnish a correct indication of relative costs, which are not likely to be fundamentally altered by slight changes in actual conditions.

The following analysis of annual cost has been prepared by Mr. Jerome Newman, formerly Chief Engineer of the Board of State Harbor Commissioners, for six different types of waterfront construction, based on pre-war contract prices. It is believed that the changes in labor and material costs of the past few years have been fairly uniform for the several types of construction considered, and that the pre-war contract prices will show the relations more satisfactorily for future use than will the erratic fluctuations which obtained during and following the war. However, any of the assumptions may be changed, and the general method still be used.

A life of twenty-five years is assumed for creosoted Douglas fir piles, based upon the service of those of the Southern Pacific Co., Oakland, Long Wharf. With good

materials, and careful installation and maintenance, this life is not unreasonable. It is assumed that in the case of each construction type the cost of construction is financed by the sale of bonds bearing 5 per cent interest and maturing at the end of the assumed life of the pier; that a sinking fund is established at the same rate of interest to retire the bonds at maturity; and that a depreciation or replacement reserve is laid aside at the same rate of interest for the purpose of reconstruction and returning loss of revenue during the time of the reconstruction. The distance from the top of the piling or cylinder to the water surface is taken at five feet, the depth of water at 35 feet, and the penetration of the piling at 35 feet. The construction costs are per square foot of deck surface.

Based on a twenty-five year life for creosoted piles, the figures show the annual cost of all types for the same length of life. In addition to this the life of all other types has been calculated from an annual cost corresponding to the annual cost of a creosoted piling pier.

ANNUAL COST, 25-YEAR LIFE

TYPE A

Creosoted piles, first cost $1.00 per square foot

Interest on investment, at 5%	$0.0500
Maintenance, at 5%	0.0500
Insurance	0.0066
Sinking fund payment	0.0209
Depreciation reserve	0.0230
Loss of revenue	0.0063
Total annual cost per square foot	0.1568

TYPE B

Reinforced concrete piles, first cost $2.00 per square foot

Interest on investment, at 5%	$0.1000
Maintenance, at 1%	0.0200
Insurance	
Sinking fund payment	0.0419
Depreciation reserve	0.0503
Loss of revenue	0.0063
Total annual cost per square foot	$0.2185

TYPE C

Reinforced concrete cylinders, first cost $3.00 per square foot

Interest on investment, at 5%	$0.1500
Maintenance, at 1%	0.0300
Insurance	
Sinking fund payment	0.0628
Depreciation reserve	0.0757
Loss of revenue	0.0063
Total annual cost per square foot	$0.3248

TYPE D

Untreated piles encased in reinforced concrete, deposited inside a wooden cylinder, first cost $1.85 per square foot

Interest on investment, at 5%	$0.0925
Maintenance, at 1%	0.0185
Insurance	
Sinking fund payment	0.0387
Depreciation reserve	0.0445
Loss of revenue	0.0063
Total annual cost per square foot	$0.2005

TYPE E

Untreated piles surrounded by pre-cast reinforced shells driven into the bottom, first cost $2.25 per square foot

Interest on investment, at 5%	$0.1125
Maintenance, at 1%	0.0225
Insurance	
Sinking fund payment	0.0471
Depreciation reserve	0.0542
Loss of revenue	0.0063
Total annual cost per square foot	$0.2426

TYPE F

Untreated piles encased in plain concrete poured above water and lowered into place, first cost $1.40 per square foot. (Derived from the cost of a creosoted pile pier by deducting the difference in cost of creosoted and untreated piles and adding the cost of the concrete protection, assumed at 60 per cent of the present price.)

Interest on investment, at 5%	$0.0700
Maintenance, at 3%	0.0420
Insurance	
Sinking fund payment	0.0293
Depreciation reserve	0.3373
Loss of revenue	0.0063
Total annual cost per square foot	$0.1813

LIFE OF DIFFERENT TYPES FOR EQUAL ANNUAL COST

Annual cost of Type A, $0.1568 per square foot
Life assumed for Type A, 25 years

TYPE B

Maintenance and interest	$0.1200
Annual payments, reserve funds	0.0368
Required at end of life:	
Sinking fund	2.0000
Depreciation reserve	2.4000
Loss of revenue	0.3000
Total required	$4.7000

Life necessary to produce this sum at 5%, 41.0 years.

TYPE C

Maintenance and interest	\$0.1800

As maintenance and interest alone for this type are greater than the total cost of Type A, it is at all times more expensive than the latter and its cost increases with its life.

TYPE D

Maintenance and interest	\$0.1110
Annual payments, reserve funds	0.0458
Required at end of life:	
Sinking fund	1.8500
Depreciation reserve	2.1275
Loss of revenue	0.3000
Total required	\$4.2775

Life necessary to produce this sum at 5%, 35.6 years.

TYPE E

Maintenance and interest	\$0.1350
Annual payments, reserve funds	0.0218
Required at end of life:	
Sinking fund	2.2500
Depreciation reserve	2.5825
Loss of revenue	0.3000
Total required	\$5.1375

Life necessary to produce this sum at 5%, 50.4 years.

TYPE F

Maintenance and interest	\$0.1120
Annual payments, reserve funds	0.0448
Required at end of life:	
Sinking fund	1.4000
Depreciation reserve	1.6100
Loss of revenue	0.3000
Total required	\$3.3100

Life necessary to produce this sum at 5%, 31.5 years.

In the above calculations allowance was made for the cost of removal by increasing the depreciation funds as follows:

10% of the first cost for Type A.
20% of the first cost for Types B and C.
15% of the first cost for Types D, E and F.

Revenue per square foot was assumed at \$0.3000 per annum and one year was allowed for reconstruction, an assumption favorable to concrete structures.

Maintenance charges were taken at 5 per cent for Type A, 1 per cent for Types B, C, D, and E, and 3 per cent for Type F. The parts most subject to wear are fender lines and deck pavements, and as the maintenance cost for these parts is the same for all types, the maintenance percentages assumed are also favorable to concrete structures.

The calculations presuppose the use of the best construction methods with resulting structures not subject to failure on account of the lack of precautions on the part of the builders.

Structural Requirements

The design of a structure is often controlled by considerations which affect its potential physical life but are quite independent of the length of time the structure is to serve, or its economic life.

An instance of this already noted is the case of ferry slips, which must be built of flexible piling. Since timber is best suited to this use, and for that purpose is commonly used untreated, such structures have a limited physical life.

Another instance is that of trestles and wharves without superstructures, in which the piling can be renewed with comparative ease. A relatively short-lived piling is likely to be selected for such structures, giving low first cost and avoiding the possibility of economic loss if changes are found desirable in the future.

Short-lived piling usually requires considerable maintenance, however, and in structures where the piles are inaccessible or where maintenance would be very difficult, the short-lived material is uneconomical and long-lived or permanent types are indicated.

The general axiom that "a building is only as good as its foundation" may be paraphrased by its converse, "the foundation need only be as good as the building"—unless there is definite assurance that the same foundation can continue to serve future conditions after the superstructure is rebuilt. If this assurance is lacking, it is likely to be assumed that the foundation can be rebuilt at the same time as the superstructure. Under average conditions the foundation should be capable of service at least equal to that of the superstructure: temporary, permanent, or fireproof buildings, as the case may be, should be supported by piling of comparable qualities.

Structural requirements may necessitate the strongest and the most permanent materials regardless of all other considerations. This will obtain in the case of seawalls, bridge piers, substructures for buildings having excessive floor loadings, and similar cases.

The limitations of available materials may eliminate short-lived types, as, for example, where the depth of water is too great for the use of available timber piling.

The conditions of exposure, such as in "ocean exposure," may eliminate short-lived material and require the strongest and most permanent available.

INSTALLATION AND CONSTRUCTION PRACTICE

Preliminary Investigation of Substrata

Test piles and borings should be utilized to ascertain the condition of the substrata. This is necessary that correct lengths be secured and the piles driven properly. It is particularly necessary where partial length protection is to be used, the portion above the mud line being protected and that below unprotected. To accomplish this the exact penetration should be known beforehand so that the protection will be carried to the proper point. Alternating layers of hard and soft strata often lead to mistakes in driving. During this operation when the pile strikes a hard layer the penetration decreases, which is normally an indication that the driving can be stopped; a moment later the pile may pass through the hard layer and sink rapidly through a soft formation. After this the pile is in danger of being overdriven with the expectation of penetrating another layer.

Such overdriving is dangerous for all types: in reinforced concrete it develops cracks through which water can enter and corrode the reinforcing steel; in protected timber piling it causes checks and flaws which open the way for borer attack and may render the protection practically worthless. Preliminary investigations will show whether or not jetting should be used, to relieve the driving and consequent effects.

Changes of Mud Line

Attention must be given to possible changes of the mud line. Where tidal or river currents are strong, investigations should be made over as long a period as possible to ascertain changes in the bottom. Possible scouring or silting due to changing currents, produced by the contemplated piling or other substructure itself, should be forecast as thoroughly as possible.

Propeller action often churns away adjacent embankments. The likelihood of future dredging should also be determined. This phase is particularly important where types of protected piles are used in which the protection is carried down only to just below the mud line.

Bottom Penetration

Where flexibility is required, yielding substrata are better than hard substrata. The former will support the pile laterally and resist some of the side thrust when the pile is flexed, in this manner distributing the bending stresses in the pile over a greater length. In hard, unyielding substrata the flexibility and maximum stresses are confined to a comparatively short length of the pile above the mud line, which often results in the breaking of piles. When such hard substrata are encountered, a greater number of piles should be driven to distribute the stress. It often happens, however, that piles are broken off at the mud line before the necessity for additional ones is apparent. In some cases rip-rap is placed around the piles to give lateral support. This must be carried out carefully, however, to prevent unequal deposit of the stone around the piles, pressing more on one side than the other, and either forcing the bottom end out of position, or bending the pile and thus creating initial stresses which may result in failure. The more common method is to place the rip-rap first and drive the piles through it. If the piles are supported vertically to any extent by friction with such rip-rap, any settlement of the latter may cause the piles to settle and create a difficult condition. In any of these cases the rip-rap must not be counted on to protect the timber from marine borers, unless it happens that the voids are completely filled with mud and silt.

Relative Depth of Water and of Bottom Penetration

Pile design is often determined by the relative depth of water and of mud penetration. Below the mud line the various types are more or less equal in value, and untreated timber, which is the cheapest form, will there serve as well as any other. If the water is shallow and the penetration great, it may be economical to apply to the piles a part-length protection, which can be carried only down to a point a short distance below the mud line, the shorter length protected overbalancing their usually greater cost per linear foot as against full-length protections such as creosoting. Part-length surface protections such as the paint and batten protections (see p. 256) are shown by our extensive service records to be shorter lived than creosote impregnated piles.

Where the water is deep, however, and the penetration comparatively small, a full-length creosote protection is initially cheaper, is longer lived, and has the structural advantage that the composition of the pile is uniform throughout its length.

The drawbacks of partial length protection methods are the difficulty of applying the protection to the correct length of the pile, and the possibility of a changing mud line. The protection must extend a few feet below the mud line to allow a margin of safety, as well as a short distance above high water. This is difficult to accomplish for those types in which, as in the paint and batten type, the protection is applied before the pile is driven, particularly because of the uncertainty as to the actual amount of penetration that will occur. The latter must be determined as accurately as possible,

and careful workmanship and driving methods used. A much surer partial length protection is obtained by types such as the precast jacket, in which the timber pile is first driven and a precast reinforced concrete shell then slipped over it and driven into position. The application of this method to the protection of wooden piles in an existing structure requires the removal of the superstructure, or at least of the flooring, and springing the piles out from under the superposed stringers. When, as in most cases, this is impracticable, practically the only alternative for piles already in place is the use of one of the methods, like the Camp process, for applying the concrete shell in short sections which are individually lowered in turn to position until the whole protection has been built up. All types of partial length protection of timber piling involve the hazard of the possible subsequent lowering of the mud line to below the protection, with the resultant exposure of the wooden piles and their destruction by borers.

Length of Pile

The distance from wharf to mud line, plus penetration distance, may be so great

Fig. 23. Handling 100-ft. concrete piles during pier construction.

that a single pile may be impracticable. On the Pacific Coast Douglas fir can be secured in lengths of 100 feet or more, which is adequate for the great majority of cases. Some of the piles used in the trestle approaches to the Dumbarton Bridge of the Southern Pacific Company were 125 feet long, the bottom penetration being 60 feet. Splices are sometimes used where single lengths are too short. The usual practice in cases of great depth is to drive a cluster of timber piles to below mud line and superimpose upon them a concrete column. Reinforced concrete piles having lengths of 100 feet or more

have been thus used in various San Francisco Bay structures. In building Pier 29 in 1916, for example, driven reinforced concrete piles 20 inches square and 106 feet long were used. For the outer 200 feet, however, the depth was so great that a single pile length would not suffice and clusters of from 6 to 9 timber piles were driven to below mud line, upon which reinforced concrete cylinder columns were superimposed.

Stresses

Piling is usually required to sustain only vertical loading. It may, however, be called upon to resist horizontal forces, as for example when serving in retaining, or bulkhead walls, dolphins, fender lines or ferry slip construction. Retaining or bulkhead walls resist a constant static load, and are usually strengthened by brace piles and ties. In other cases mentioned the function of the pile is to create a spring to absorb the impact shock of boats striking the structure. This is illustrated in the case of ferry slips where speedy operation is required. The ferryboats must enter the slips quickly; the first contact is with the fender piles, which resist the impact until they come in contact with the back structure, which in turn is flexed and the boat brought to rest, the fender and wharf piles thus taking up the shock gradually, so as not to injure the boat. Current and wave action exert great forces on solid substructures, but as far as actual stresses created in piling is concerned they seldom need be considered. Their adverse effect is upon the material which goes to make up the piling.

All elements of a pile must be capable of functioning under these stresses without rupture of any part. Concrete cannot be used where flexibility is required; and if timber is used, its protections against marine borers must adjust themselves to flexure without deterioration.

Handling Piles

All precautions against adverse influences after placement of piling may be nullified by careless handling before and in the placing. This would seem an obvious fact, common to every material and form of construction, and yet all evidence shows that it is far from fully appreciated in regard to timber piling. Especially after having the piling preservatively treated is it equally important that it be carefully handled from the treating plant to the job. Once the outer protective shell is penetrated, the value of the pile is largely destroyed, except for possible repair; the borers, especially *Limnoria*, will take advantage of the smallest openings to the untreated interior wood. The danger is increased by the fact that such damage due to mishandling may not be apparent until some time after the construction is completed.

Of the creosoted piles driven in structures of the Long Wharf, 13,000 pieces, or about 93 per cent were treated at the Southern Pacific Creosoting Plant at West Oakland and, therefore, received a minimum of handling to the job, yet an average of about 30 per cent of the piles in the structure were subjected to attack by marine borers on account of physical damage to the protective shell. The extent of damage is likely to be in direct relation to the extent to which it is necessary to handle the piles. On San Francisco Bay, at present, it is necessary to purchase all of these materials from distant plants, involving a maximum amount of transportation and handling and consequent damage. Being so far from the source of supply, it is necessary to keep creosoted piling on hand at all times, which also adds to its chances of being damaged before being used. All of this handling and storage makes it very difficult to avoid damaging piles.

The survey of wharf substructures made by the Board of State Harbor Commissioners in 1922, which has already been quoted, showed that the dog is by far the worst

enemy of creosoted piling in this region. In one of the early years of this Committee's work there was under observation a pile-driving crew in this Bay, with a raft of creosoted piling dogged across the center of the raft (fig. 24). As the raftsman worked the piles out of the raft up to the driver, he drove dogs into the piles at five different points in their length. It has been a common sight to see rafts of creosoted piling dogged

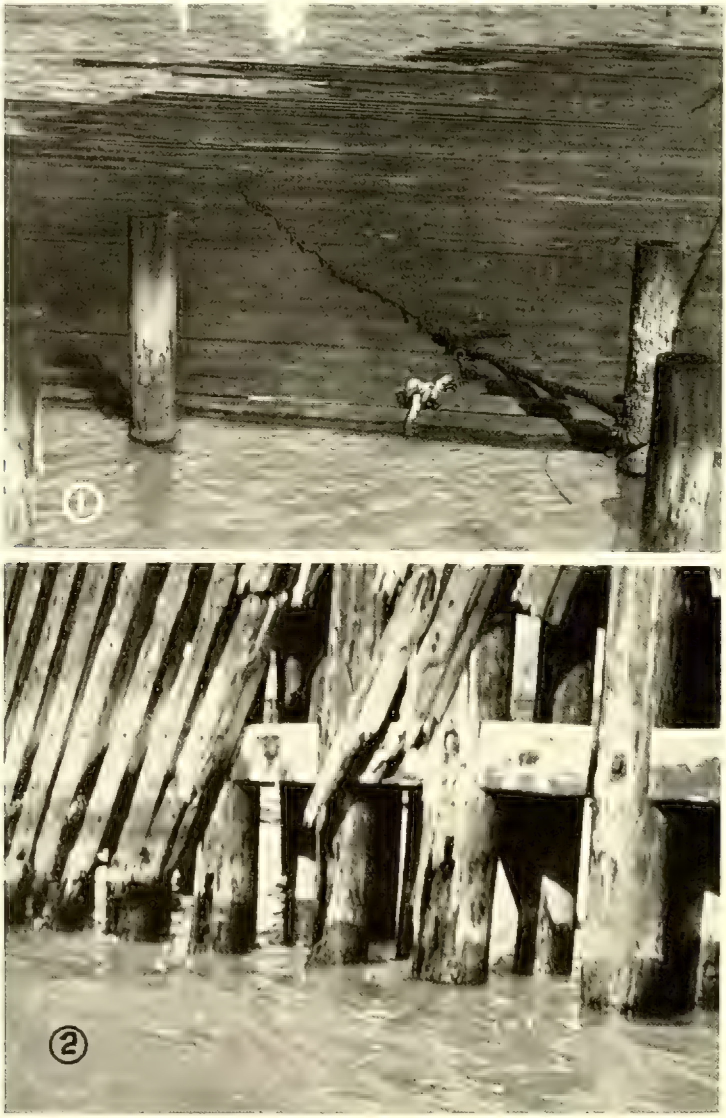

Fig. 24. (1) A raft of creosoted piles chained together by means of rafting dogs. Untreated wood will be exposed to borer attack when the dogs are pulled out, wherever the holes come within the water section of the piles.
(2) Creosoted ferry slip piling, attacked by *Limnoria* where creosoted zone was cut through in construction.

diagonally across, each pile being permanently damaged, as the holes made by the dogs were seldom plugged. The use of dogs should be unconditionally prohibited, except within specified distances of either end of piles, which will allow ample margin to protect the water section of the piles. When creosoted piles are prepared for towing

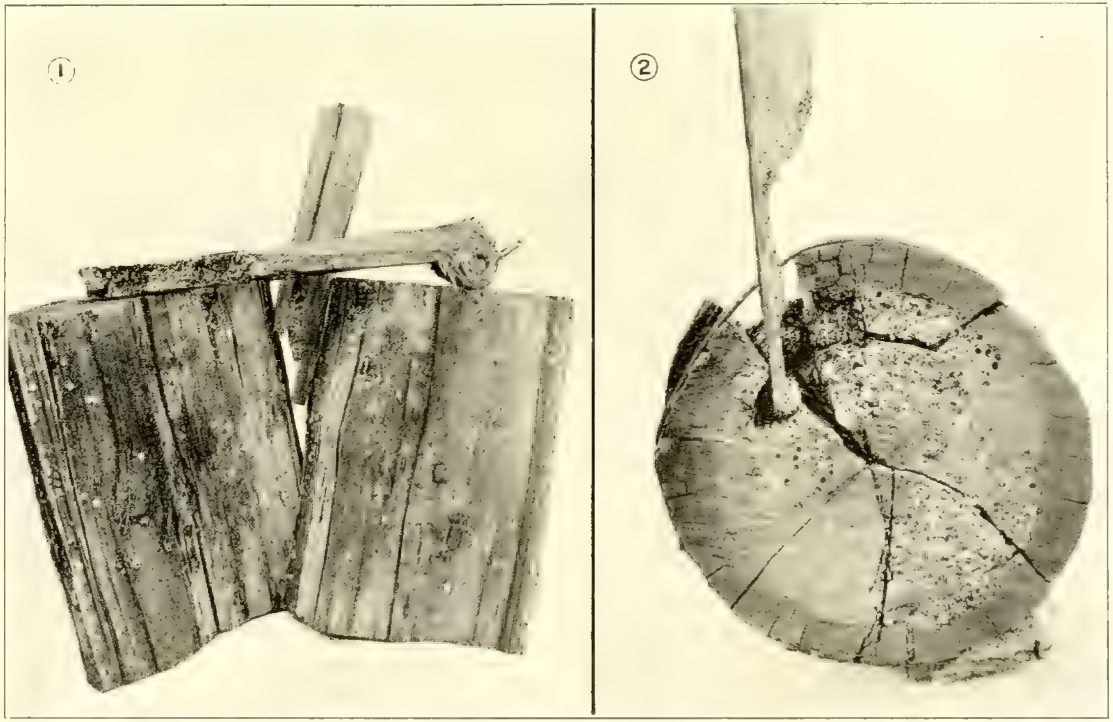

Fig. 25. (1) Vertical section, and (2) cross-section through portion of a perfectly treated pile which was split and broomed during driving. *Teredo* entered splits and worked through untreated heartwood to the creosoted outer shell, which was attacked in a few spots as shown by smaller pieces.

a considerable distance, boring and reeving should be the only method of fastening allowed.

The ax, the pike pole and peavie also cause much damage. The holes left by sinking an ax into the piling, as is frequently done in handling, are much like those caused by the dog, and are particularly dangerous. The use of pike poles and peavies should only be permitted when their points are blunted. The use of boat hooks during inspections by row boat or raft is also a source of considerable damage to treated piles in place, and should be prohibited.

Driving

With creosoted piling, again it is necessary to take precautions against the puncturing of the protective shell with pike poles, peavies, axes, etc. Unfortunately men handling creosoted lumber and piling seldom appreciate the necessity for preserving the protective shell. Eternal vigilance is the price of a good job in this respect.

Closely allied to this, one of the most important duties of the pile-driving crew, to drive the piles without puncturing the protective shell, is the necessity of care against the always present danger of checking the piling under the hammer. In using a steam hammer it is well to use piles of a butt diameter of at least 14 inches. This permits the pile to be headed, so that the plate upon which the plunger strikes has a sufficient bearing entirely on wood whose fibres, below the surface, are supported on all sides by surrounding ones, and it is therefore not so likely to cause checking. On rocky bottoms, where there is little or no mud, great care must be taken not to split the pile (fig. 25). This can be done by avoiding hard driving, and by the use of various types of steel shoes and plates.

Much the same precautions apply to the driving of concrete piling as to that of wooden piling, overdriving causing similar, although not, of course, identical troubles.

Bracing

The conditions of flexure in the pile will further depend upon its length from wharf to substrata, the pile acting as a column with either or both ends fixed. With unsupported lengths averaging from 30 to 50 feet from wharf to substrata, it becomes desirable to reduce this length by cross bracing. This however has been found impracticable, except to a minor degree. Timber piling protected against borers should not be braced below the high water line for the reason that the framing or other connections of pile bracing will rupture or weaken the protection and the way will be opened for borer attack. Metal pile connections below high water have been found to corrode and break, and connections in concrete piles are likely to develop cracks and expose the reinforcing bars to corrosion, with resultant disintegration of the concrete and destruction of the joint. As a result, bracing, as well as ribbing and other attachments should be made above high water level. (see fig. 24). This restriction of bracing to the restricted space between top of pile and high water, or even wave splash level, is a severe handicap upon mechanical rigidity. For creosoted piling, batter piles having their connections above high tide level will be found the most satisfactory means of securing bracing of the required rigidity.

Cutting and Framing

Creosoted piling should not be cut off below high water line, thus exposing untreated wood to attack by borers, if it can be avoided. Even tide slopping, where piling is cut near to high water level, may permit *Limnoria* attack, if water can settle where it does not run off (fig. 26). Furthermore, decay frequently occurs in the untreated interior of piles when they are cut off at any level above high water. Whenever

piles are cut off, therefore, the untreated wood should be protected by thoroughly painting the top of the cut-off portion with hot creosote. Above the water line, a further coating of thick asphalt may be applied, to prevent the penetration of moisture; below water line the access of borers can be prevented by covering tightly with sheet copper.

Dapping the piles, which exposes untreated wood, should be prohibited except where it is absolutely unavoidable. If structural members are to be framed into timber

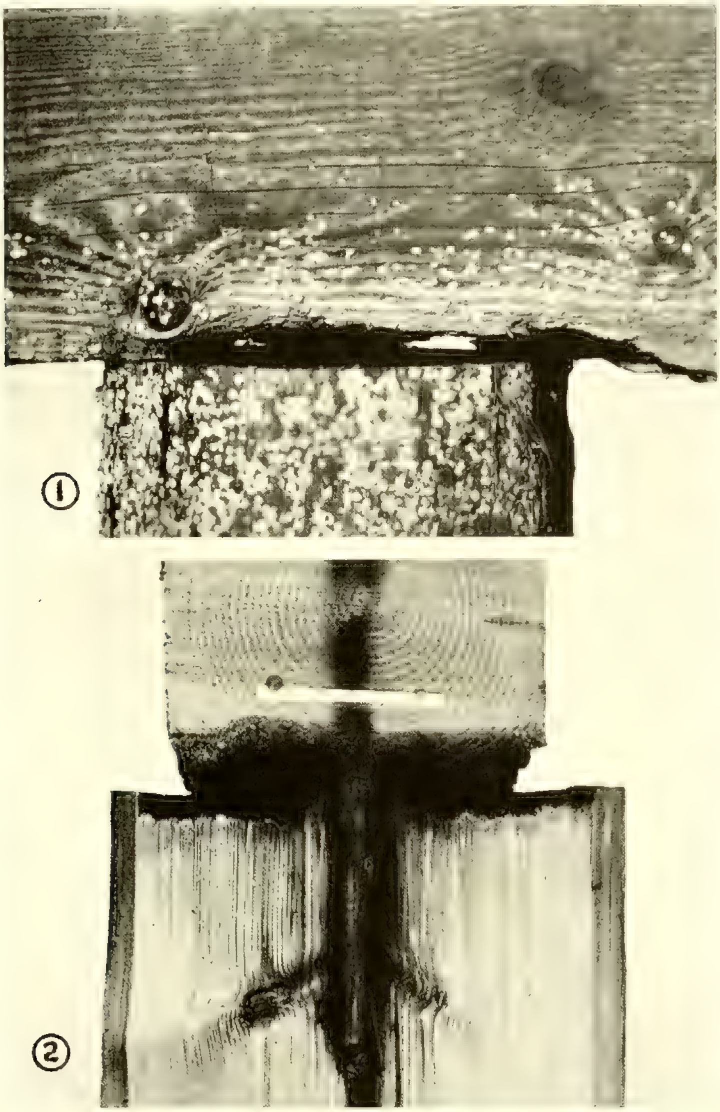

Fig. 26. (1) Creosoted pile cut off too close above the water. *Limnoria* attacking top of pile and the corbel. High water point is indicated by the barnacle line.
(2) Section vertically through center of pile head and corbel shown in 1. Note the creosoted shell not yet attacked.

piles, the necessary cutting or framing should be done, as far as possible, on the pieces to be attached to the pile, since they are cheaper to renew (fig. 28). All such attachment members should be creosoted if they will be exposed to borer attack, and all

boring and framing which can possibly be done in advance should be made before the members are creosoted.

This recommendation of framing (including bolt holes) before treatment is the one most often objected to as impracticable, or impossible or too costly. Actual and continued trial has proved it practicable, at least on most ordinary construction on San Francisco Bay, where, except for one company, all creosoting must be obtained from a long distance. In ordinarily simple construction, bents can usually be sprung

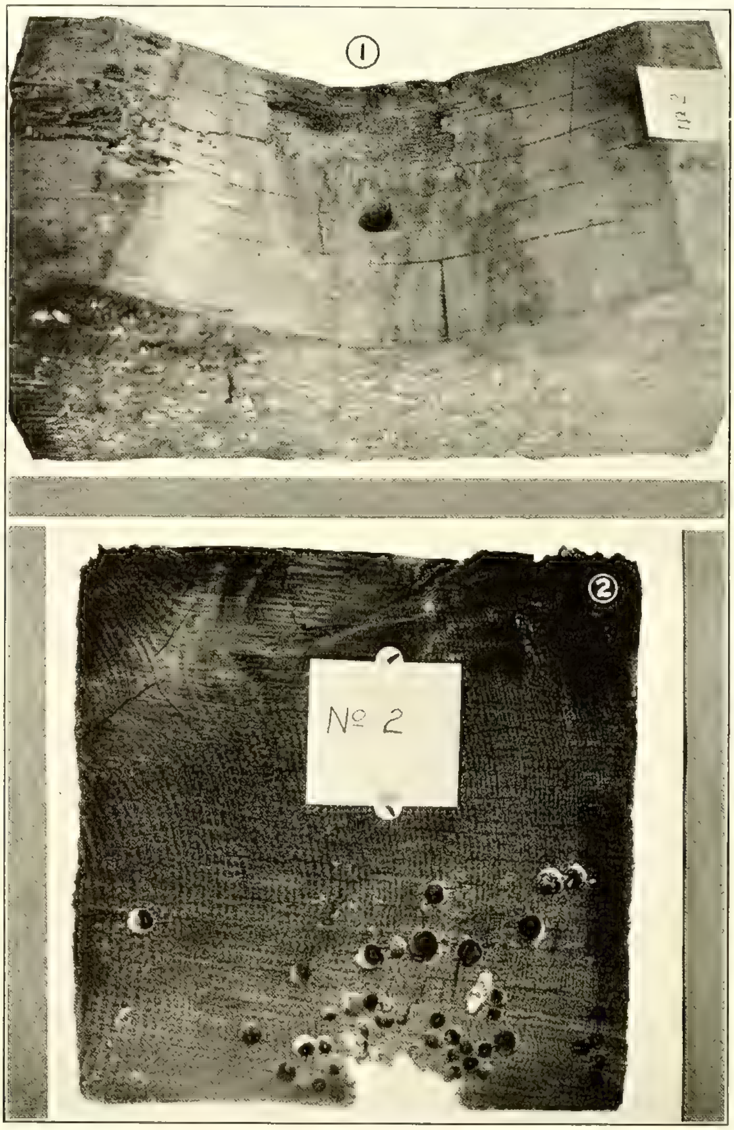

Fig. 27. (1) Section of creosoted girt, in which untreated wood was exposed in framing.
(2) End view of same girt section as in 1, showing attack by *Teredo* which entered through the untreated wood exposed by framing.

enough to make such framing fit. It adds somewhat to the construction cost; but its results are believed to justify its cost.

When framing before creosoting of timber is impossible, all bolt holes should be

filled with hot creosote and framing cuttings should be well swabbed with it before putting the parts into construction. All holes for ordinary bolts or for pins should be bored not larger in diameter than the bolt or pin, to insure a driving fit. This will prevent borers from entering the bolt holes, so far as it is possible to provide against it (fig. 28). Where machine bolts are used, however, the holes should be bored $\frac{1}{16}''$ larger than the diameter of the bolt.

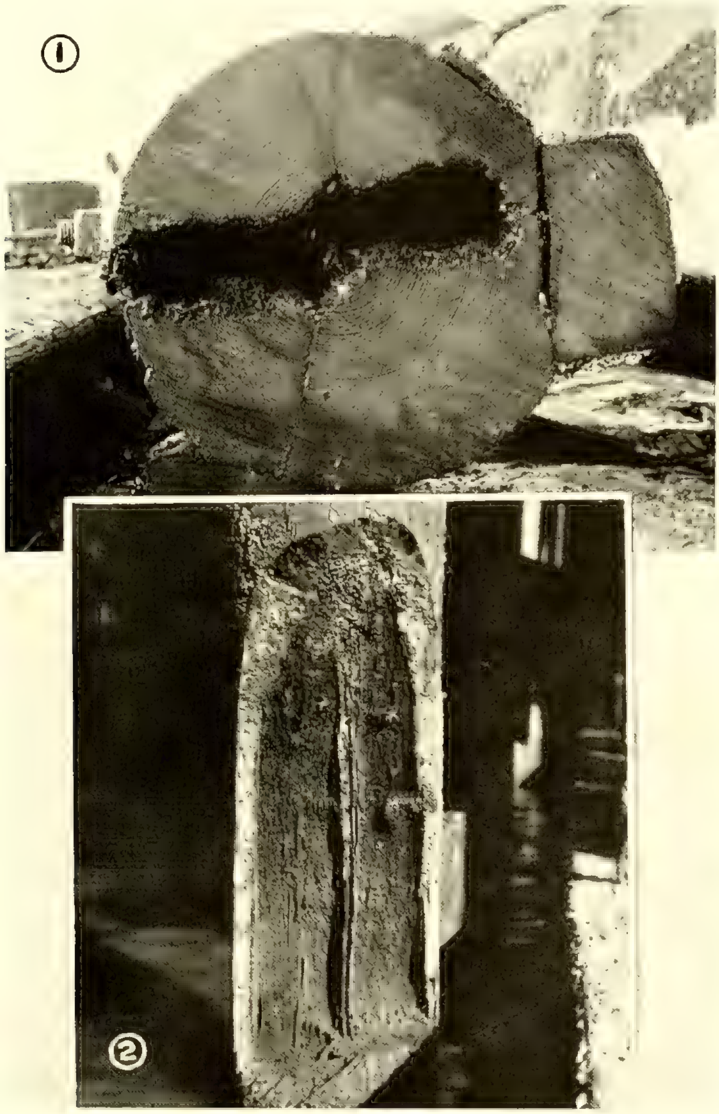

Fig. 28. (1) Bolt hole in creosoted fender pile, enlarged by *Limnoria*.
(2) Creosoted pile, attacked within five years by *Limnoria* in a spot exposed by chopping.

The Flooring System

The flooring system is of sufficient importance to deserve more attention than is many times given to it. Timbers for the flooring system should in all cases be as heavy as can be used within economic cost. A careful study has convinced this Committee that, after all framing and other cutting has been done, it is both a most desirable and

most profitable practice to give all such timbers a light impregnation of, say, 6 lbs. per cubic foot, of creosote.

Cut-offs, corbels and caps should, if at all possible, be placed not only above high tide but above the zone of wave slop, which, as has been noted, is dangerous in respect to *Limnoria* attack wherever water can stand without running off. (See fig. 26). Whenever this is not feasible, they should at least be heavily swabbed with hot creosote. For corbels and caps a light pressure treatment of 6 lbs. of creosote per cubic foot is recommended.

If it is not desired to use creosoted timber for the floor system in a dock, care should be taken to ventilate contact surfaces and to give them as thorough a treatment with creosote as possible. Hot creosote swabbed on plentifully during construction is the best treatment available under such circumstances.

It is very desirable to place a watertight covering, such as a two-inch surface coating of asphalt, over the deck of wharf structures. Such a coating makes a satisfactory floor surface, gives additional fire protection and keeps surface water from seeping into the wooden floor system.

Fender Piles

Because fender piles take the impact and friction of vessels, they are subjected to severe usage and their life is limited, often to a comparatively few years. Because of the flexibility required, fender piles are usually of timber, and in cases where ships come in direct contact with the piles and the life of the latter is thus limited by mechanical wear, untreated timber is commonly used. If, however, the mechanical wear can be reduced, treated timber can and should be used. Practices now tend toward protecting fender piles with sheathing, or with blocks or stub piles bolted between the piles and projecting beyond the face of the latter, to take the contact with the ships and serve as wearing surfaces. Such protections are less expensive than full length piles and can be renewed with comparative ease. In all cases, fender piles should be placed so that they can be renewed readily.

Wearing surfaces for ferry slips usually consist of diagonal sheathing, while those for wharf fender piles are commonly made of untreated sawn timbers or stub piles placed alternately with the fender piles and extending from about low water level to the wharf floor. The hardness of Eucalyptus, together with its supposed natural resistance to borers, has led to its use where mechanical wear is involved. It has proved successful for fender stubs; but when driven full length it has often been broken off because of brittleness, and it has been found to be readily attacked by borers. (See p. 91.)

Fire Hazard

Concrete provides the most effective substructure material where a definite fire risk is involved. This value is often considered to justify the added expense of concrete construction. The cargoes stored on wharves often have a value much greater than the structures themselves and added protection is as necessary here as in land structures. If the superstructure is fire-proof the substructure should be likewise. Numerous instances are of record of waterfront conflagrations caused by burning materials floating on the water surface. Harbors where oil is handled extensively involve a particular hazard in this respect. Wherever timber piling is used ample provision should be made for quickly reaching all parts of the substructure, by means of trap doors in the wharf floors. In many instances this is required by city ordinances.

Inspection

It should be obvious that specifications and inspections should be co-extensive. The best specification is comparatively valueless unless inspection is both thorough and of sufficient scope to insure that the specification has been complied with.

DURING CONSTRUCTION

Under present conditions, in which workmen are for the most part comparatively untrained in the intricacies of preparing and handling substructure materials, the only means of securing successful results is through painstaking supervision by those who understand the problems. Careful specifications should be prepared to cover all phases of the work and constant inspection should be established to see that they are followed. Timber, its protections and treatment methods, cement, and concrete aggregate, all involve special requirements which must be made the subject of specification and of inspection check. The Committee believes that the best insurance of right results in respect to the furnishing of creosoted piling is to have inspection for final acceptance done as it hangs in the driver gins, where every defect may be seen and examined. On the practicability of such a requirement see further under The Problem of Workmanship (p. 82). Similar attention must be given to the placing of materials in position. Piles must not be prematurely damaged by over-driving; protective shells for timber piles must not be broken or penetrated; concrete must be properly mixed and placed.

AFTER CONSTRUCTION

When a structure is completed it commonly is allowed to continue in service with little or no attention until it gives evidence of failure. Yet through inspection the life of the structure can often be prolonged, sometimes greatly, whereas otherwise it may fail suddenly, with loss of life and property. Where timber piling is involved, the effect of borer attack should be closely watched; if the timber protection is only carried to the mud line, a periodic investigation should be conducted to make certain that the mud has not been removed below the protection; if flaws develop they should be repaired as quickly as possible, because of the numerous influences which are ready to hasten deterioration. Inspection by ordinary means can be effectively made only above low water level. Under specially favorable circumstances this may suffice to indicate conditions. However, where property of critical importance or magnitude is involved, the inspection should be made by a diver to give accurate information of conditions down to the mud line. When such an inspection is made in a structure involving a great number of similar piles or other supporting units, it may only be necessary to select certain representative units, to determine the average or general condition.

TEST BLOCKS

Where unprotected timber piling is serving in water in which an infestation by marine borers may occur, especially in isolated structures where no attack has been experienced, a particular hazard is involved. Procedures should be adopted to note the advent of the borers and to observe the degree of their attack. This offers some difficulties, however, for the reason that when such action begins it is not readily detected and may escape a casual inspection. Surface erosion by *Limnoria* is very minute and gradual, yet destruction may occur in the period between inspections if the first attack is missed. The presence of *Teredo* and *Bankia* is particularly hard to observe because of the microscopic size of the holes in the pile surface through which they enter the timber and destroy the interior. This condition is often further obscured by barnacles and shell fish adhering to the surface. Since the degree of attack

of these two borers can be determined only by viewing the interior of an exposed timber, cutting into the wood is required; this must always be avoided if possible with protected piling. A convenient substitute is the test block. These can be exposed in any number and at any point and if properly used will give a reliable indication of attack.

Conditions under which test blocks should be placed have already been discussed under the subject of Infestation (p. 56), with reference to the instructions for systematic preparation and exposure of such tests in Appendix B.

The Problem of Workmanship

The great body of adverse influences affecting a marine structure, together with the exacting conditions of its operation, obviously require that the best materials and workmanship be used in its construction. Yet, what is "best" must always be conditioned by what is practicable; it is easy to conceive of a substructure capable of meeting all requirements, yet which would be impossible of general use because prohibitive in cost of construction. The best of workmanship can only be, therefore, the best that can be economically justified. In other words, procedures must be developed whereby successful results will be obtained with the best workmanship that is feasible.

It has already been noted that many substructure materials which have failed could have been successful had proper workmanship been used. An instance of this is afforded by the so-called Holmes cylinder, consisting of one or more timber piles encased in a cylinder of concrete. This type, built in Pier 5 at San Francisco in 1896, is still serving after 29 years, whereas many complete wharves built subsequently with the same type have long since failed and been rebuilt with other types. The life of wharves built with this type, with the exception of Pier 5, ranged from about 7 to 15 years. Pier 34, built in 1910 with a substructure of single piles encased in concrete, is still serving in perfect condition after 15 years. These two instances of successful results have been attributed to careful methods of placing the concrete, the several unsuccessful results to faulty methods of average workmanship. The practical difficulties involved in securing successful results have caused the type to be at least temporarily abandoned, although it is not inherently faulty (fig. 29).

Another phase of the problem of workmanship concerns especially the common handling of jobs by contract. Contract crews are even more likely than the owner's own employees to be ignorant of the damage caused by carelessness, and thoughtless of loss thus entailed. Besides this, if specification requirements in respect to workmanship are unusually difficult or onerous, the contractor may fail to carry out the work accordingly, through his own failure to understand, his inability to train his men, or his deliberate intention. Much can be done to help, by personal explanation and discussion, as a supplement to specifications or instruction orders, especially with respect to care in handling, and it is time well spent for an engineer to seek in this way to enlist the cooperation of rafting and construction crews. Improved methods of inspection are increasingly eliminating deliberate evasion of specification requirements and concealment of shoddy work; but the problem of perfunctory or cursory inspection still requires eternal vigilance. Inspection of piling in the gins, which has been recommended, takes more time. It is thus likely both to be opposed by contractors and evaded by inspectors, and can be secured only by continuous insistence. However, its results are worth the cost.

Additional cost, if any, must of course be paid for; but if requirements are plainly stated in the specifications upon which bids are taken, all bidders are on the same footing. Contractors cannot afford to scrap valuable material, such as piling, which

they have bought in good faith under previous conditions of practice, because of new restrictions. In the case of creosoted piling the increased cost of getting new requirements fulfilled will be lessened, as well as the danger of having rejected piling slipped in again, if provision is made for the acceptance of piling when properly repaired after rejection because of dog holes or similar injuries.

The difficulty in bringing about improvement in handling and construction prac-

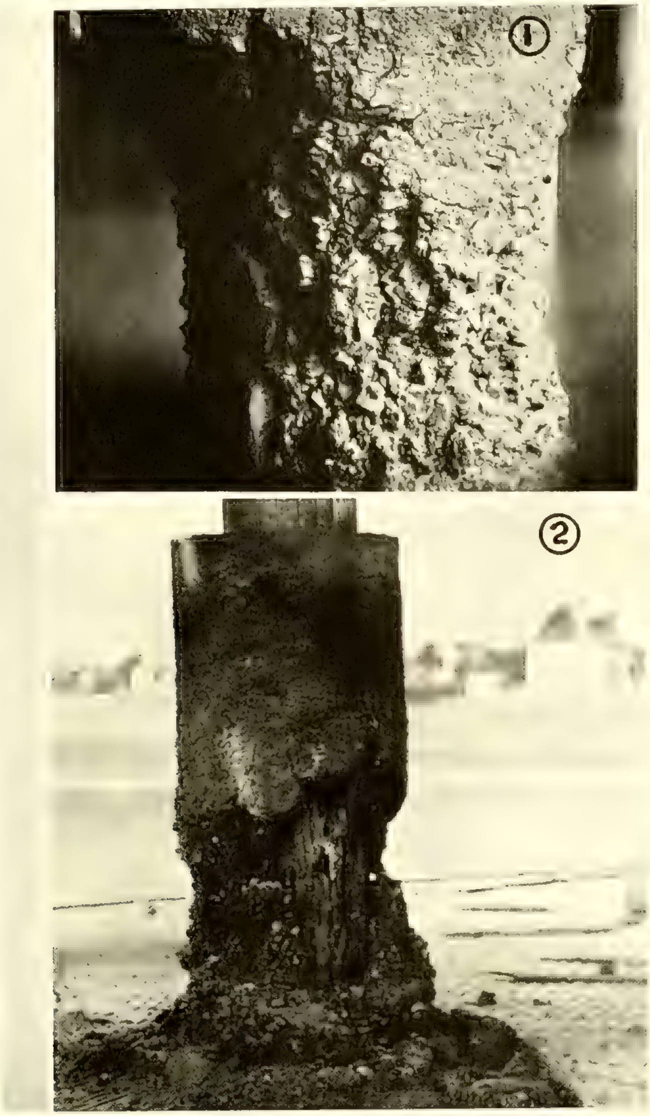

Fig. 29. (1) Disintegration in concrete composite pile. Probably a result of poor workmanship.
(2) Disintegration in concrete jacket placed on pile previously covered by battens and paint. Pile attacked by *Limnoria* where coverings have failed.

tice is due, not only to the difficulty of training workmen in new ways of doing an old job and to lack of understanding by workers of the nature and seriousness of the damage caused by carelessness, but equally to lack of understanding by managements both of these things and of the large returns it is possible to realize through care,

over and above the comparatively small increased cost necessary to secure it. Informative effort addressed to those responsible for the financial control of projects is often highly profitable in respect to the improvement of construction results.

For the reasons cited above, substructure design must be such that it can be executed under average practical conditions by the available quality of workmanship and it must be simplified as far as possible. Even so, every effort will be necessary to secure the most careful workmanship, and constant attention as well as intelligent and conscientious inspection will be required.

Repair

Reference has already been made to the fact that the life of piling can often be prolonged many years by properly repairing it from time to time. Several methods of accomplishing this have been developed to serve various conditions. In creosoted piling, holes made by dogs, pike poles, etc., or any others of small size and regular form should be plugged with creosoted plugs. Larger holes or those of irregular shape, such as those in creosoted piling attacked by borers, have been repaired by filling with cement mortar when above low tide level or by covering the holes with layers of saturated felt and sheet copper securely nailed. Yellow metal used instead of the latter has been found to corrode too rapidly. When copper is used it must be thick enough to allow for some surface corrosion.

The Southern Pacific Company has successfully repaired creosoted piling by the latter method, using two layers of saturated felt and a sheet of copper, the work being done both between tides and below water, as follows:

A supply of repair patches in the various sizes which have been found most commonly required is prepared in advance. The layers of felt and the sheet of copper are stuck together with hot asphalt so that the patch can be handled as one piece, and the perimeter is punched for nail holes. The pile is cleaned of barnacles and other forms of sea life, and the holes to be repaired are located and measured for patches. The proper sized patches are then selected and immediately applied. In this way the work is accomplished expeditiously and efficiently. Repaired piles have in several instances been removed and the repair work done below water has been found to have been perfectly carried out.

Concrete spalling or cracking above low water can be repaired by pointing or by using gunite. (See further p. 129.) If deterioration of a substructure member is general a concrete shell may be cast around it.

Removal of Breeding Grounds—Harbor Sanitation

A borer infestation is maintained solely through the presence of exposed unprotected wood. One pile may harbor 150,000 teredos, each capable of producing 2,000,000 larvae to attack other piles. The Bay is so thoroughly seeded up that every floating fragment of wood is likely to be infested to its capacity. Yet it is not uncommon for structures attacked by borers to be abandoned and left standing until they collapse, large masses of the structure and clusters of piling floating away. This is not only a menace to navigation but provides the means of spreading the infestation. Such material establishes a menace equal to fire hazard. It is to the interest of every owner of a marine structure to eliminate such wood as far as possible, and if property owners avoid taking proper action themselves, laws should and eventually will be created to enforce it which may result in greater expense and restriction than if the matter had been handled voluntarily.

The use of unprotected timber piling should be avoided in waters which are

infested or subject to infestation; if an untreated structure is built to serve temporarily it should be completely removed as soon as possible. Similarly driftwood and unused or abandoned timber of every description should be removed.

Borer attack thus can be greatly reduced and infestation often rendered negligible and perhaps eliminated, by the general adoption of protected types of piling and by a thorough program of marine sanitation.

Records

The problems involved in marine structures must largely be solved by individual owners for their individual conditions. Knowledge of the subject is in a state of development and will continue to be so for a considerable time. The particular nature of the problem involves study and investigation covering many years, often a period longer than that in which the organization of the original builders remains intact. For this reason, records of essential details and conditions should be established and maintained in order that past procedures may be judged as a basis for future work. Knowledge of probable life and cost is essential for an intelligent selection of materials. The only means by which such information can be developed is through records of individual concerns. A majority of structures are modified and rearranged in the course of time, and all such work can be greatly simplified if general data have been kept on them.

CHAPTER VIII

MARINE SUBSTRUCTURE MATERIALS

To the engineer responsible for the design, construction and maintenance of structures in sea water, accurate information on the nature, relative cost, effectiveness and permanence of various kinds of piling and pile protections is of the greatest importance. The lack of such information prevents a close estimate of the probable annual cost of structures on piling of different kinds and must result many times in the adoption of uneconomical materials or methods. There is no way to estimate accurately the money value of information of this kind, but when the amount of damage done by marine borers in recent years is considered, or even the annual expenditures in normal years for new construction and repairs, it is obvious that information resulting in but very slight improvement would permit savings of very considerable sums of money.

Following are descriptions of the more important piling and pile protection materials and methods used in San Francisco Bay and tributary waters, with discussions of their value on the scores above mentioned. Statements respecting permanence, especially in respect to those materials or types of piling in which that quality is a function of resistance to borer attack, will be understood as applying only to the conditions of this Bay or conditions closely similar to them. These statements rest upon a very large body of service records gathered by this Committee, whose tabulation in detail will be found in Chapter IX.

UNTREATED TIMBER PILING

Some species of timber form ideal piling material in respect to form and working qualities. Such an ideal timber should be straight, of regular cross section, strong without excessive weight, resilient, of small taper, available in long lengths when needed, abundant in quantity, and relatively cheap. Ideal quality should also, however, include natural resistance to marine borers and other destructive agencies. There is no species of wood native to North America which is naturally immune to such attacks. There are a number of foreign species for which immunity is claimed, some of which are commented on further in this report; but in every case these are at present either too expensive, or the supply is too limited or uncertain, to permit their use on anything but an experimental basis in this harbor.

Fig. 30. Green test pile driven at west end of Alameda Distributing Station Dock in December, 1920. Pulled November 27, 1923. Depth of water at high tide 25 feet. Original dimensions of pile 40 feet long, 14-inch butt, 8-inch tip.

Pile broke off two feet above mud line when pulled.

Three inches of sound wood remaining from mud line to lower high water.

Practically all destruction by *Limnoria;* a few *Sphaeroma*, and no evidence of *Teredo.*

Three old *Bankia* burrows found, near mud line, only.

Douglas Fir

On the Pacific coast this timber species holds for piling purposes a position of supremacy similar to that held in the southern and eastern United States by Southern pine. This is due to its superior excellence, as compared to other timbers here available, in practically every one of the qualities which have been named—form, strength, available lengths, quantity obtainable and moderate cost. It has no natural resistance to any of the marine wood borers, so that it must be artificially protected from their attacks; and to injection by preservative chemicals, which is the most common method of protection, it presents very considerable refractoriness. That, in spite of

Fig. 31. (1) Untreated Douglas fir pile from Oakland Municipal Quay, east of Grove Street sewer, driven 1913, removed October, 1920. Destroyed at mud line by *Bankia*, surface eroded by *Limnoria*.

(2) The same, end view.

these points, it is so nearly exclusively used is evidence of the degree of its superiority in other particulars.

One point illustrated by the case of Douglas fir is so often overlooked as to be worth emphasis. Not the least of the merits of Douglas fir, as a species, for piling use, is its relative cheapness and the fact that its available supply on the Pacific coast is greater than that of any other species whatever. Species have been repeatedly recommended to the Committee and are advocated for use, like the cottonwood and the alder, which, whatever their technical merits, could not be found in accessible and available stands of suitable form to supply by any possibility the current demand. Conceivably there might be cases where Douglas fir or other preferred species might

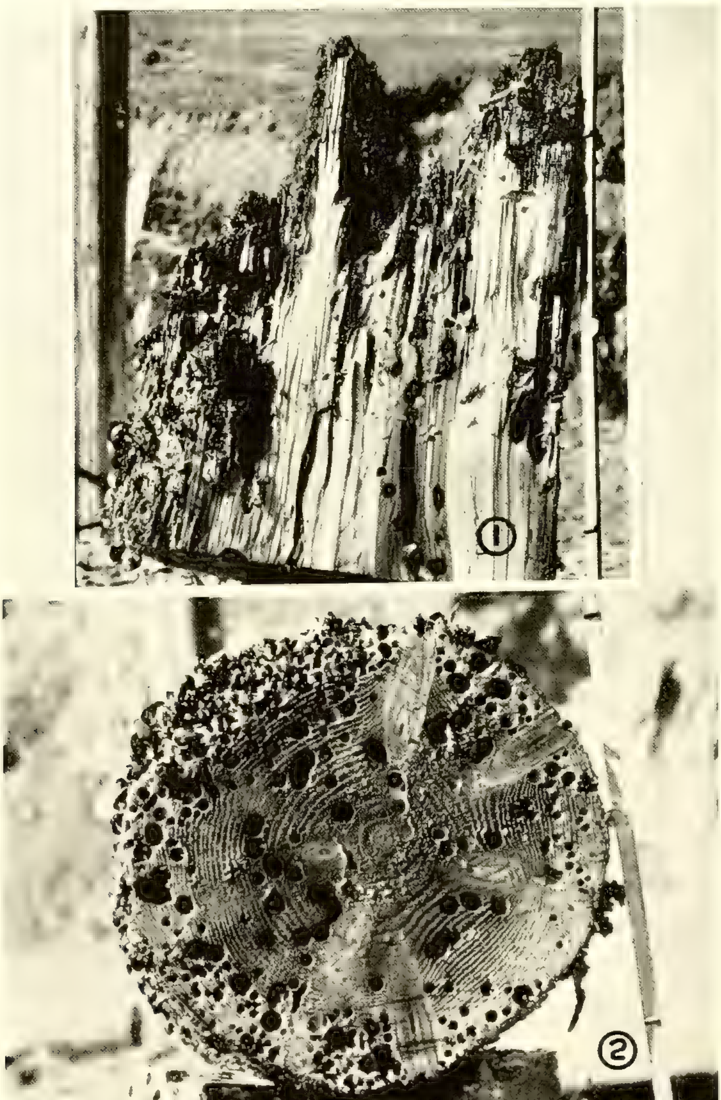

Fig. 32. (1) Dolphin pile from Richmond Municipal Pier, driven December, 1917, broken out July, 1920. Note large tubes of *Bankia* and smaller ones of *Teredo navalis*, and erosion by *Limnoria* at breaking level. *Sphaeroma* also present. Breaking zone exposed at low tide.
(2) Section of same pile, one foot above break.

be locally unavailable; or the knowledge to be gained from experimenting with other woods might be the controlling factor. But aside from such exceptional cases, it may be laid down as a general rule that a timber can have no practical value for piling purposes unless it is available in sufficient quantities for general use and at a cost commensurate with the service to be secured from it.

Records show that unprotected timber piling of the original San Francisco wharves was destroyed in from 3 to 5 years and was probably unserviceable after 3 years. This same condition prevails today, with many instances of complete destruction in a single season.

Destruction is most rapid near the Golden Gate. Elsewhere in the Bay longer life may be secured because of local conditions. That the results to be obtained with untreated piles are directly governed by their exposure is illustrated by the experience of the San Francisco-Oakland Terminal Railways (now the Key System Transit Co.). In 1902 this company built a long trestle of unprotected timber extending into the Bay from the Oakland shore. No other structures existed to the north except a few small minor wharves, and the nearest to the south was Oakland Long Wharf, about a mile away, built of creosoted piling and practically free of borers. The structure was unmolested for about five years. Not long after that the borers were found to be at work, and their attacks continued with increasing severity until in 1913 thirty unprotected timber anchor piles were destroyed in a single season. Since that time it has been necessary to use treated piling in the structure.

This would seem to indicate that an untreated pile structure in a location isolated from structures known to be harboring marine pests can be expected to last considerably longer than an untreated pile structure in close proximity to structures known to be infested. This is true in spite of the fact that the marine pests are present at all times. Untreated piles are also more severely attacked at the outer end of piers, or in deep water, than they are inshore or in shallower water. Unusual local conditions may affect the attack, as shown by the experience of the Howard Co. with gas plant wastes discharged nearby, discussed on p. 57.

Redwood, Port Orford Cedar, Western Red Cedar

These closely allied woods have been and still are frequently asserted to be immune to marine borers. They are not. There is some evidence tending to show rather greater resistance than in some other woods; but the evidence is often conflicting. These woods are not as strong as Douglas fir for general piling use. They are not infrequently used, however—especially redwood in this region—in collateral or special construction exposed to marine conditions. In one case redwood conduit pipe carrying into the bay water which had a temperature of over 135° F. was not only attacked by teredo but the pests were able to follow this pipe for over a thousand feet and destroy the redwood tank with which it connected, far from tidewater, so severely as to make necessary its practical replacement.

Cottonwood

Cottonwood piling has been widely reported to have given very long life in wharves in Alaska, the life thus far secured being reported in two cases as 10 and 28 years and the water known to be thoroughly infested by marine borers. There are no available data establishing the exact species of timber used there, and the inference that it may have been some other timber, or that the data themselves were in error, is suggested by the quite opposite results secured in experiments made by the Chicago, Milwaukee & St. Paul and Northern Pacific railroads at Seattle and by the Southern Pacific Co. at

Oakland, Calif., as well as by this Committee. Further doubt of the asserted results with Cottonwood is occasioned by the report of the Alaska Packers Association to this Committee that they have secured only a 3-year life from this timber in Alaska and are contemplating creosoting it in the future.

The species of cottonwood common to the Pacific coast and doubtless that used

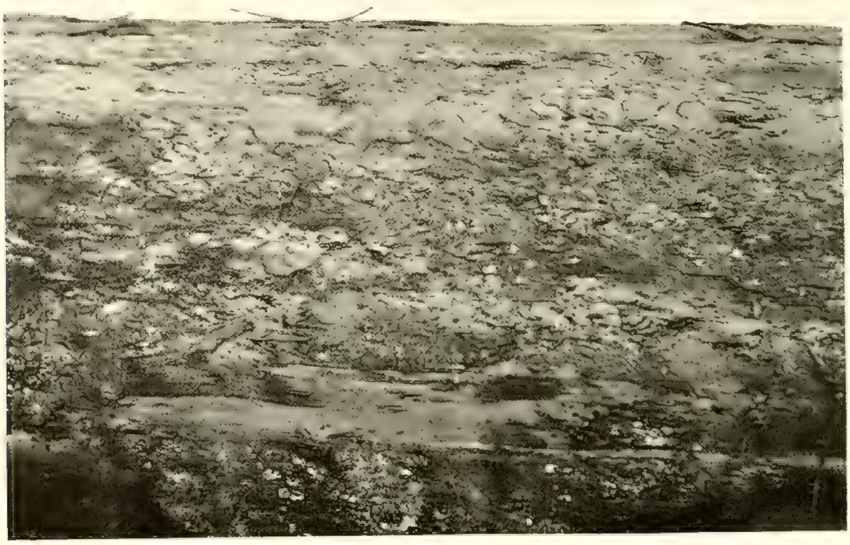

Fig. 33. Redwood pile from Fort Mason, attacked by *Linmoria*.

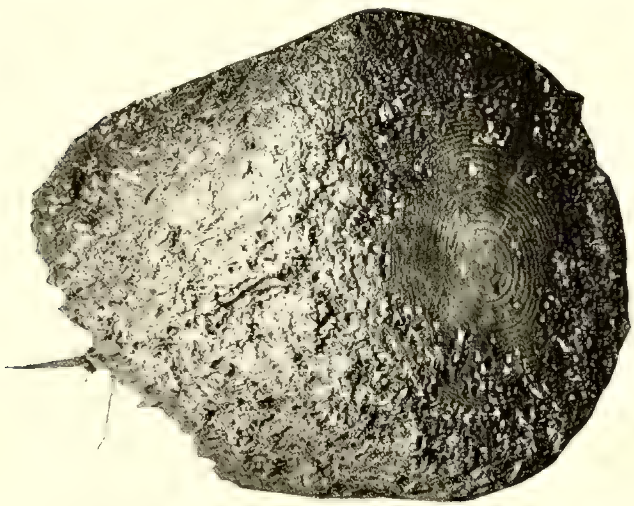

Fig. 34. Section of cottonwood pile exposed less than six months in San Francisco Bay.

in the experiments of the railroads mentioned is known as "Black Cottonwood" (*Populus trichocarpa*). The total stand of this black cottonwood on the coast is relatively limited. Its form is much less desirable than that of the Douglas fir, and its inferiority as a timber for structural purposes is shown by the following comparison with Douglas fir:

COMPARISON OF PHYSICAL PROPERTIES OF BLACK COTTONWOOD AND DOUGLAS FIR

(From U. S. Dept. of Agriculture Bulletin 556)

	Black Cottonwood	Douglas Fir
Weight per cu. ft., green (lbs.)	46	38
Weight per cu. ft., oven-dry (lbs.)	20	28
Moisture content (percent of oven-dry wt.)	132	36
Tension fibre stress at Elastic Limit (lbs. per sq. in.)	6,200	10,600
Compression parallel to grain at Elastic Limit (lbs. per sq. in.)	4,410	9,260
Compression perpendicular to grain at Elastic Limit (lbs. per sq. in.)	460	1,220

In August, 1923, several 4-foot lengths of cottonwood were submerged for test purposes at the Committee biological station at Oakland Pier. While this was about a month too late for the heavy breeding season of *Teredo*, the specimens were found to be attacked quickly by both *Teredo* and *Limnoria*, that of the latter being general. The final inspection of October 10, 1924, showed extremely heavy attack by *Limnoria*, and additional attack by *Teredo* and *Bankia*, some of the latter having attained a length of 18 inches.

In October, 1923, 30 cottonwood piles were placed by the Southern Pacific Company at 7 wharf locations in Oakland and carefully observed at about 3-month intervals. These were placed too late for the 1923 breeding season of *Teredo*. However, they were immediately attacked by *Limnoria*. The final inspection of October 10, 1924, showed extremely heavy attacks by *Limnoria*, the erosion being to a depth of about 1¾ inches. Attack by *Teredo* and *Bankia* was found in a minor degree, probably due to the fact that the *Limnoria* had taken complete possession of the pile surface.

The evidence of these tests shows that such piling will be completely destroyed in from 2 to 3 years and that, even if obtainable, it can in no way be justified for use in marine structures where Douglas fir is available.

Eucalyptus

There are more than two hundred species of Eucalyptus. Among them are some which, like the Australian Jarrah (*Eucalyptus marginata*), ironbark (*E. sideroxylon*) and grey box (*E. hemiphloia*), have a high reputation for their resistance to marine borers and their general suitability for piling purposes. The most common one in California, and the only one in fact at all widely available, is the blue gum (*Eucalyptus globulus*).

Blue gum Eucalyptus is very heavy, hard and strong, comparing when sound with American hickory, except in elasticity. In exposed use, however, such as piling, it shows an abnormal tendency to split and check, both under initial driving and under subsequent weathering and impact of boats. In 1909 about 1200 piles of this species were driven in a San Francisco ferry slip. These failed within 4 years, either from borer attack or from checking and breakage. Of the large number used in the original trestle of the San Francisco-Oakland Terminal Railways (now the Key System Transit Co.) a few still remain in place in the car storage trestle stub after at least 12 years' service. These are of course the exceptional ones which resisted destructive checking. In respect to the borers, the known fact that the conditions at the Key System piers on the Oakland side of the bay are much less favorable to *Teredo* and *Bankia* than are

those on the San Francisco side, while *Limnoria* is much less unfavorably affected on the Oakland side, would seem to indicate from the above records that blue gum Eucalyptus resists the attack of *Limnoria* better than does Douglas fir, but that of *Teredo* and *Bankia* little if any better.

The quantity in which blue gum Eucalyptus is available in piling size and form is too restricted and uncertain to make it a large factor in that situation, even if more highly suitable than it is. For wearing blocks, or stub piles, usually extending down to about low water only, and bolted between the standing piles of the spring line to take boat friction and other wear, mechanical life is short in any case. The great hardness and toughness of the ecualyptus gives it excellent serviceability for this use, which is now expanding. For this purpose the supply is probably adequate.

Foreign Woods

As has already been stated, the foreign woods, of which there are a considerable number which appear to have specific resistance to marine wood borers, are none of them at the present time able to meet on a competitive basis the cost of the creosote treated Douglas fir pile. Marvellous tales are current respecting the life of some of these foreign woods in borer infested waters, and in some cases appear to be supported by credible evidence, e. g., 75-year life of turpentine wood in the Philippine region, and of manbarklak in piers at Maracaibo, Dutch Guiana. The test made of some such woods by the Committee was, of course, much too short to disclose anything significant. In the following partial list, the woods thus tested by the Committee are starred. Test result comments following these species, referring to the Committee exposure tests, can be followed in detail by reference to the tabulations in Chapter XI.

FOREIGN WOODS CLAIMED TO BE RESISTANT TO MARINE BORERS

From African Kamerun:
- *Azobe (*Laphira procera*). Unattacked in Committee test.

Australian or New Zealand woods:
- Totara (*Podocarpus totara*)
- Matai (*Podocarpus spicata*). *Podocarpus elata* also said to be resistant.
- *Turpentine wood (*Syncarpia laurifolia*). No attack.
- Grey box (*Eucalyptus hemiphloia*)
- Ironbark (*Eucalyptus sideroxylon* and *E. paniculata*)
- Jarrah (*Eucalyptus marginata*)
- Red gum (*Eucalyptus rostrata*)
- *Tallow wood (*Eucalyptus macrocorys*). Showed slight attack in two years.

Philippine woods (in order of resistance):
- Liusin or Cretalingan (*Parinarium corymbosum*)
- Aranga (*Homalium luzoniense*)
- Betis (*Bassia betis*)
- Dungon (*Tarrietia sylvatica*)
- Dungon late (*Heritiera littoralis*)
- Molave (*Vitex parviflora*)

South American woods:
- *Greenheart (*Nectandra rodioei*)
  Slightly attacked in three years in Committee tests. Attack moderately heavy in nine years in Forest Service tests at San Diego. Said to have failed seriously in Panama Canal work.
- *Manbarklak (*Eschweilera corrugata*)

Not attacked. Resistance is due to silicious crystals in the cells, rather than to an alkaloidal poison as in the case of greenheart. This doubtless makes the resistance of manbarklak more permanent. The wood is, however, excessively heavy and hard, being impossible to work with ordinary steel tools.

*Toledo wood (See manbarklak).

Durability of Untreated and Unprotected Wood

The value of any method of protecting piling or of any substitute for wooden piling depends upon the life which can be obtained from the protection in question as compared with that of untreated, unprotected wooden piling. In a region as large as San Francisco Bay and its tributaries, where the water conditions vary from the freshness of river water to ocean salinity, and from the extreme contamination by sewage and factory wastes from great cities to the relative purity of ocean water, it is to be expected that great differences will be found in the durability of untreated piling in various locations. The life of native species may vary from as little as six months at the point of worst borer infestation, to as much as 4 or 5 years in specially isolated

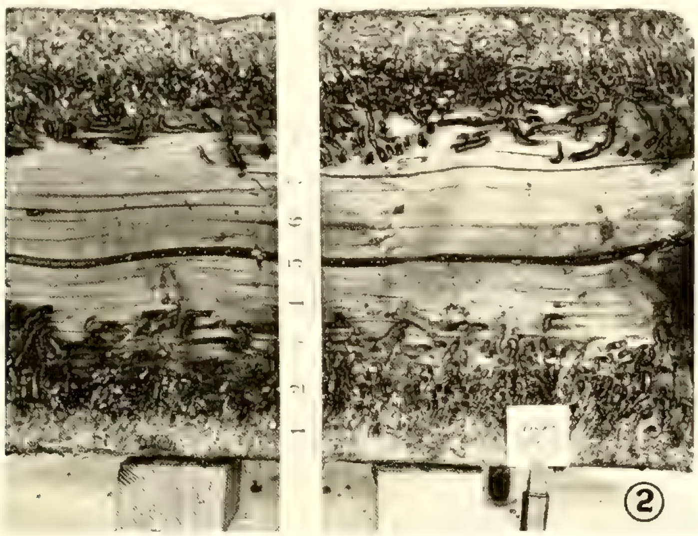

Fig. 35. Green Douglas fir pile driven at Mooring Z, Mare Island, on August 14, 1920, and pulled December, 1920. *Teredo navalis* had penetrated four inches in this four-month interval. (*U. S. Navy Photo.*)

or protected localities. This assumes ample salinity of the water. Going up the Sacramento River or elsewhere into increasingly fresher water, one can, of course, find all degrees of diminishing intensity of attack. In the biological part of this report, other factors are discussed which influence the distribution of the several borers and the severity of their attack.

It is significant that of the several thousand untreated wooden piles taken under observation by this Committee in 1920 (after the teredo had been working in the Carquinez Strait region for three years or more) every one had been torn out or replaced by the end of the following year, except some which in the meantime were salvaged by the concrete jacket method.

Untreated piles, unprotected, still have their use in temporary marine structures,

but extreme care must be used in investigating local conditions. The principal thing to be noted is exposure to attack: see tables of salinity for the locality; note proximity of infested structures. Protection by local contamination, which may in some cases prove an unfavorable environment for pests, is, however, most unsafe to rely upon (see discussion of this factor, p. 57 ff). The purpose for which a structure is to be used will determine whether it will have outlived its usefulness prior to the time of anticipated collapse.

EXTERNAL PROTECTIONS FOR WOODEN PILING

The need for protecting piling against marine borers has aroused the interest and the inventive genius not only of those directly concerned with the building and maintenance of piling structures, but of a multitude of others. Numerous devices, materials and methods have been suggested. Some of them have been so impracticable that their only value has been to demonstrate the ignorance of their sponsors concerning the results of past experiments and the requirements of a pile protection. Some of them, on the other hand, have considerable merit and extensive experiments with them have been justified.

All the suggested external protections which have come to the Committee's attention may be placed in one or other of the following classifications: bark, metal nails and sheathings, paint and paint combinations, concrete jackets, and miscellaneous devices or processes. Concrete protections for wooden piles, however, are discussed in the general consideration of concrete, as a matter of coherence in the treatment of that subject.

Bark

The early discovery that bark, at least in some species, was not attacked by marine borers as readily as the wood led to the belief that the former could be counted on as a protection. Its use became standard practice about the year 1869 and piling specifications of the years following that called for piling timber having a complete bark covering. Furthermore, since bark adheres to the wood more firmly in winter than at other seasons, it was required that the piles be winter-cut.

Early investigators of the 70's reported that . . . . "the teredo . . . . never eats the bark of wood, and only enters the piles after the bark has been removed," and further that—"piles are attacked by the teredo as soon as the bark falls off, which is in about two years after they are driven . . . . " This indicates that they considered that bark increased pile life about two years.

These statements are quoted as a matter of interest rather than for their accuracy. At best, however, the bark is in danger of being knocked off in patches during the hazardous course of the pile from the stump to its place in the structure. Unless all such piles are scrupulously rejected, this exposes the wood in spots and permits immediate attack at those points. Borers working in these patches soon enlarge them by burrowing under the surrounding bark. The softening action of the water, coupled with the abrasive action of driftwood and waves tear off additional bark and soon the pile is in a practically unprotected condition. Furthermore the borers are not entirely repelled by the bark. Specimens of bark were secured from piles during this survey which show large burrows of shipworms.

A company at Richmond in 1920 reported concerning their past experience, "Where bark is kept intact this class of pile lasts from four to five years in this locality."

In Forest Service experiments made at Fort Mason in San Francisco Bay, and at San Diego, experimental pile sections of unbarked western hemlock showed attack within six months, both by *Limnoria* and shipworms. The attack began in patches

where the bark had been broken off in the handling. In two years the *Limnoria* attack in one specimen was 1¾ inches deep, and some *Bankia* galleries 30 inches long and ⅝ inch in diameter had developed.

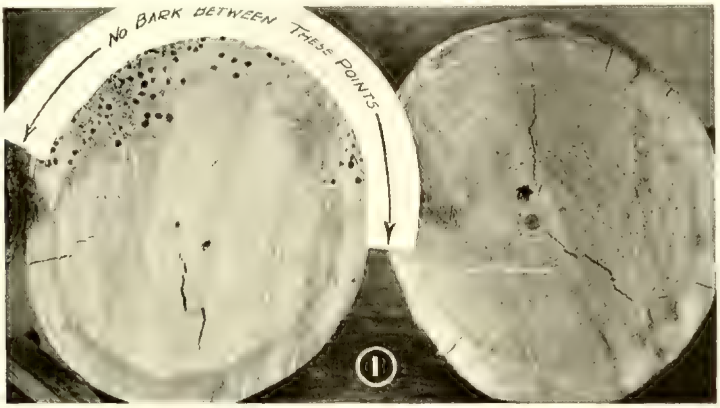

Fig. 36. Pile from Associated Oil Co. wharf, Port Costa, driven with bark on, presumably in 1910, removed in 1921. Borers attacked where bark protection was damaged.

It cannot be definitely stated that bark covered piles have never given good results, but the evidence which has come to the attention of the Committee indicates that the additional life to be expected by leaving the bark on is uncertain and not over one or two years.

METALLIC PROTECTIONS FOR WOODEN PILES

Scupper Nailing

An ancient method of protecting exposed wood is that of driving flat headed nails into the wood so as to practically cover the surface with metal. In some cases the nails are spaced so that the heads cover only a portion of the surface—possibly 50 per cent—it being expected that the formation of rust will sufficiently cover the exposed wood, and that the nails in the interior will retard the borer action.

In San Francisco Bay the borers have been found to attack rust impregnated wood around bolts and nails; the interior borers simply change their course to miss the metal obstruction; with repeated heavy infestation the wood is thoroughly honeycombed, and the *Limnoria* completes the destruction, if it does not begin it. The Santa Fe Railway and the Spreckels Company used this type of protection in structures in San Diego Bay built in 1881-3 and 1898 respectively. Some of the piles are still in place and serviceable. They have since discarded it for other types of piling; but the superintendent originally in charge of the experiment for the Santa Fe Company says it was only because of the prohibitive rise in the cost of the boy labor employed in the nailing. The method has undoubtedly some value, but this is not sufficient to be compared with that of other available protections, and the method has now no importance except as a matter of record.

Sheet Metal

Metal sheathing has been used since ancient times to cover wood exposed to marine borers, particularly ship bottoms. Iron, zinc, yellow metal and copper have been used for this purpose. Of these, the first is comparatively unsuccessful because of rapid corrosion; zinc and yellow metal are very expensive and corrode in a short time; copper is likewise expensive, but its rate of corrosion is less than that of the others and it has given good service in many cases.

The earliest recorded use of copper sheathing in San Francisco Bay is that of a group of piles driven in 1870 in the U. S. Army Pier No. 1, at Alcatraz Island. With reconstruction and repair these remained in service until 1907 when they were encased in concrete.

The Northwestern Pacific Railroad has used piles sheathed with copper and with yellow metal under its docks at Tiburon and Sausalito. Some of these were used as early as 1884. The detailed records concerning these piles are not available, but it is reported that, in the main, they gave long life. Some trouble due to the metal being torn by drift or by thieves is reported, but there was no trouble from scour.

The Northern Pacific Railroad is stated to have driven some copper sheathed piles in a wharf at Tacoma in 1877 which remained in good condition until the structure was removed in 1898.

A company which constructed a wharf at Richmond in San Francisco Bay in 1903-4 with copper sheathed piles reports the following:

> "These piles were green, well stripped, all knots and projections cut off and finished to a smooth surface. From a point, when driven, about two feet below mud-line to a point above high water, a heavy saturated felt was applied and nailed on. In turn this was covered with 16 ounce sheet copper closely nailed with copper nails. The work was neatly done and had a very nice appearance, was at that time a little more expensive than creosote and no doubt was an excellent protection against the teredo. It has its disadvantages in the following ways: the copper being a light material, striking and floating objects would tear it, bay pirates would cut it off, and changes in depth of water due to wharf construction changing tide rips would remove silt below copper covering and allow teredo to enter."

Several hundred of these piles were driven. About 440 of them had a concrete jacket placed around them in 1908, because the mud had washed away from the bottom, exposing wood below the copper. At present, the remainder of the original copper sheathed piles are still in service without having had additional protection, and they appear to be in good condition.

The Southern Pacific Company used yellow metal for making repairs on piling of the Dumbarton bridge in San Francisco Bay but found that it corroded readily, and thereafter substituted copper for it.

This type of protection with copper as the covering material can give good service, with a life of 20 years or more, when used under proper conditions. While the cost of copper is high it need only be applied to the portion of the pile from high water to a few feet below the mud line. The disadvantages of the method are that the mud line may be lowered by scour, thus exposing unprotected wood; there is great danger of puncturing and tearing the covering during handling and driving or by the abrasive action of driftwood and boats after installation; and the value of copper often causes it to be torn off and stolen.

PAINT AND COMBINATIONS OF PAINT WITH OTHER MATERIALS OVER WOODEN PILING

The use of various paints, or applications painted on, to preserve wooden piling, is among the earliest means to be tried, and one of the most persistent. Tar and asphalt have been most often used, but they are shown by experience to be of little, if any, value so applied, at least without special treatment. At the Mare Island Navy Yard an experimental pile which had never been in salt water, and which was brush-

coated while clean and dry with hot asphalt, grade D, on July 14, 1920, was pulled on October 18th following, and found to be heavily attacked by teredo to a depth of as much as two inches. It was plainly apparent that the teredo had almost everywhere gone through the asphalt coating itself, and not simply through abrasions or other accidental openings in it. On another pile, where the action of the asphalt itself could be better observed by reason of the pile being wrapped with burlap saturated with the asphalt, the latter was found to have emulsified during the three months, in the outer four of twelve layers.

Paints Alone

A considerable number of hydrocarbon compounds intended for brush application are now being actively promoted, in which the hydrocarbon base has been so treated chemically that it remains viscous and elastic almost indefinitely, and to which have been added various poisonous constituents to kill any animal or vegetable growth which attempts to penetrate them. The promoters of such surface applications which have no additional mechanical reinforcement or protection, forget, however, the battering of vessels, or of driftwood under storm action, to the hazard of which a pile in service is subjected as well as to the boring animals. As soon as any portion of the paint protection is thus removed a door is thrown wide open to the borer. None of these methods has been given any real experimental trial in San Francisco Bay, although in experiments elsewhere some of them are said to have resisted ship-worms over periods during which untreated wood beside them was destroyed.

"Paint and Batten" Methods

A great variety of protections have been suggested and tried in San Francisco Bay, which consist of some heavy paint such as has been described, usually combined with special poisons, and applied in combination with burlap, felt, roofing paper, wire mesh, wood battens or other materials. The object of these combined materials is to reinforce the paint coat, and make it less likely to be broken or torn off. The protections of this class differ among themselves as to the nature of the paint employed and the materials and methods used in applying the reinforcement. The details and methods of applying any one of them have also varied somewhat from time to time as market conditions, opinions of engineers and the experience gained in placing the protection, driving the piles and observing their behavior have indicated that changes were desirable. They are all similar in principle, however, and possess similar advantages and disadvantages.*

The chief advantages of paint and batten coatings are their relative cheapness, ease of application and the possibility of limiting the protection to the part of the pile exposed to the borers. It has been common practice to apply the coating so that

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*The Committee understands that this general method of protection is not patented. This understanding is based in part upon the following statement which was made a number of years ago by one of the interested companies:

> "The materials used by us are not patented, nor is the method, although both materials and methods were patented. The patent on the materials has expired, while that on the method was declared invalid, hence materials and method are open to the world."

From this it would appear that, aside from the patents which may still exist on certain recently developed formulae for prepared paints, this method of protection is available for the use of anyone. The Committee has not attempted to investigate the patent situation, however, and does not pretend to speak with authority on this subject.

it will extend from two or three feet below the mud line to a point above high water. The proportion of a pile which must be coated will therefore depend on the length of piling required to get a good bearing, and the depth of the water. In soft bottom in shallow water it may be necessary to protect but a short portion of the pile. The cost per pile may then be quite low, although the cost per lineal foot treated is in practically all cases higher than that of creosote treatment.

The chief disadvantages of protections of this kind is the ease with which the surface coat of paint may be destroyed and the battens exposed. Rubbing together in the raft, careless handling and other mishaps during driving, or battering by drift-wood during storms after the piles are in place may very easily scale off patches of paint or even portions of the battens themselves and the materials beneath them. Barnacles and mussels, developing in crevices and raising the covering are a contributing factor. When the battens are thus uncovered, borers attack in the bared spots, enlarging the area, destroying the battens and exposing the material beneath. Experience seems to show that without the protection of battens the burlap and paint coating underneath is soon destroyed. Wire mesh quickly fails from corrosion when its bituminous covering is damaged. It is highly important therefore that piles protected by such coatings be handled and driven in such a manner as to cause the least possible damage to the surface. No precautions, however, can relieve such piling from the danger of storm battering. It has also been found that in many cases failure was due to the exposure of unprotected wood as a result of the rotting and disintegration of the burlap. This apparently is likely to happen much less quickly when the paint or other compound is applied to the burlap cold than when it is applied hot. In the latter case there is danger of the burlap being burned, and its rotting or disintegration is hastened by the degree to which its fibres are thus injured. When hot asphaltic or bituminous compounds are applied to wet piling, as they often have been in some of these processes, no sufficient adhesion is secured and they are in danger of peeling off as soon as the surface is broken.

A further factor affecting the value of these coatings, which is common to all external coatings applied to only a part of the pile, is the danger of unprotected wood being exposed to borer attack at the bottom. This may happen either by a miscalculation of the necessary length of driving, and therefore of protection, or by changing currents subsequently scouring the bottom away to a point below the protection. The latter may easily occur without being observed and the untreated wood thus exposed be damaged to a dangerous extent without warning.

The Northwestern Pacific Railroad in 1920 installed about 250 piles protected by the paint and batten process in a bridge trestle across Petaluma Creek under conditions which illustrate the practical applicability of this type. These, briefly stated, were: (1) lower initial cost as compared with creosoted piles; (2) possibility of salinity being so reduced by a return of wet years, and increased fresh water flow, as to kill off marine pests; (3) possibility of structure becoming obsolete before the expected life of pile would be reached; (4) sheltered location.

Durability

The records of the thirty years or more during which piling protected with paint and batten coatings has been used in this region should give considerable information as to their effectiveness. Unfortunately, however, most of the installations of piles of this type which should give this information have been removed for other causes than failure, without records being kept which would permit of adequately following them up in new locations where many of them have been driven. Accurate data are

lacking therefore on most of the installations. The records which the Committee has been able to obtain are given in the Service Record tabulation. If piling is properly treated by these processes and is not damaged by careless handling, and if its use is limited to locations protected against serious storm action, a life averaging from five to eight years may be obtained. In certain cases a life of several years more than that above given has been secured; but this has not yet been shown to be dependable. Unless the above precautions are observed, not even the average life given can be expected.

Abandoned Processes

The Key West Armor Process was a process reported to have been used in 1889 on piles for the Fremont Street wharf, San Francisco. The process consisted of painting the piles with bituminous matter, wrapping with 9-ounce canvas, and fastening the canvas on with nails 4 inches apart, applying another coat of bituminous compound and finally coating with coral sand. The results were not satisfactory, the protection lasting only about three months. So far as is known, the process was never used again.

The Perfection process was sponsored by a Mr. H. L. Rood. Piles protected by this process were installed in several locations on the San Francisco waterfront in 1894. The process consisted in mounting the pile in a huge lathe and wrapping it spirally with burlap, which was wound on to the revolving pile from a cauldron of hot tar or asphalt in which it had soaked. To hold the burlap in place a heavy wire was then wound around the pile in a reverse spiral. The wire soon cut through the burlap, which fell away and left the pile exposed to borer attack. The process was finally abandoned.

Paraffine Paint Process

This process, controlled by the Paraffine Companies, Inc., has been in use to some extent since 1889. In 1892, 1151 piles for the Powell Street pier, San Francisco, were coated by this process, and there have been numerous installations since that time. The details of the treatment of the Powell Street piles are not given, but in 1911 the following specifications covering their process were furnished to the U. S. Forest Service by the Paraffine Paint Company (now the Paraffine Companies, Inc.). This description is given, and the process rather fully discussed, as being in the opinion of the Committee, fairly representative of the better protections of this class which are still on the market.

> "The piles having been delivered in some convenient place for coating will first be barked the distance they are to be protected and all knots and projections on the above mentioned part of the pile removed.
>
> "The barked portion of the pile will then be given a heavy coat of P. & B. Pile Paint, care being taken to fill all checks and to cover all surfaces thoroughly. P. & B. Pile Covering will then be closely fitted around the pile, and all laps well cemented with P. & B. Paint and nailed with $1\frac{1}{4}$ in. galvanized nails, not more than $1\frac{1}{2}$ in. between nail centers. Where necessary a double row of nails will be driven. This pile covering will then be given a heavy coat of P. & B. Asphalt, into which will be imbedded a close fitting lagging of redwood battens, 2 in. by $\frac{7}{16}$ in., nailed on alternate edges with six penny galvanized wire nails, not more than 9 in. between nail centers, ends of battens to be double nailed. This lagging is then to be given a heavy coat of P. & B. Asphalt, care being taken to fill all spaces between battens and to give the finished surface as smooth an appearance as possible.
>
> "As above finished the pile will be ready for removal and driving."

Concerning the "Pile Covering" the following information was given:

"The material used by us is a heavy jute burlap, weighing either 10 or 15 oz. to the yard, 33 in. wide, according to the engineer's specifications—the heavier weight being that preferably used. This is saturated and coated with a specially prepared asphalt and backed with saturated felt. The heavy grade pile covering weighs about 60 pounds to the 100 square feet, while the lighter weighs about 45 pounds to the 100 square feet."

The exact nature and composition of the paint and the asphalt are, quite naturally, not given. The asphalt is understood to be applied to the burlap cold.

During 1920, 252 piles were covered by the Paraffine Paint method by the Northwestern Pacific Railroad for use in the renewal of trestle approaches to the drawbridge over Petaluma Creek at Black Point. The length of these piles ranged from 75 to 107

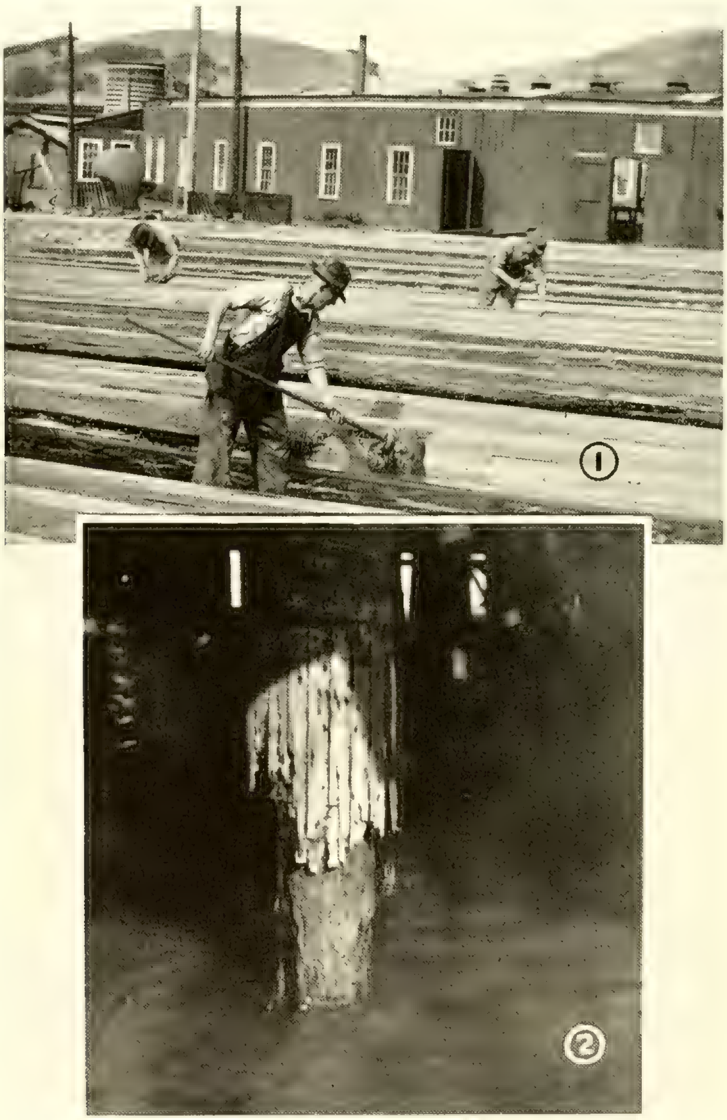

Fig. 37. (1) Piling protection being applied, Paraffine Paint method. N. W. P. R. R., 1920.
(2) Pile originally protected by paint, felt and battens, destroyed by *Limnoria*.

feet and they were covered for an average distance of 32 feet, being the distance from a point above high water line to 10 feet below the mud line when driven. The bark was first removed from the portion of the pile to be covered, then a coat of P. & B. pile paint was applied. Over this, P. & B. pile covering was placed and over the pile covering a hot coat of "Floatine" (an asphalt base paint), then ½ in. x 2 in. redwood battens and finally another hot coat of "Floatine." The protection was applied by the Northwestern Pacific Company at a cost of 62 cents per lineal foot of pile covered. There was an additional cost of $5.93 per pile for taking the piles out of the water for treatment and rolling them back afterwards.

This method of protection was adopted for this structure for the following reasons: The estimated cost per pile was materially less than the estimated cost of creosoted piles; the old trestle of untreated piles had been in place at this point for 33 years and so far as ascertainable the marine borers had not molested it prior to the last two years, and it was believed that with the return of a normal winter rainfall, the salinity of the water in the stream would be sufficiently reduced to exterminate borers. It was believed that it was reasonable to assume that conditions existing for 31 years would be restored before the temporary protection afforded by this method of treatment had deteriorated to such an extent as to permit damage by the borers. From experience with piles protected in the same manner and driven under wharves at Tiburon by the same company about twelve years before, it was believed that this treatment could be counted upon to protect the piles for from five to eight years. There is but little driftwood or wave action in the stream to cause abrasion. Moreover, because of the difficulty of satisfactorily bracing a timber trestle on account of the depth of water and the increasing wheel loads, it was presumed that this structure would be rebuilt with concrete and steel within a period for which the method of treatment adopted might reasonably be expected to furnish protection against the marine borers in the event they should remain in this stream permanently.

In 1921 the Southern Pacific Company drove 107 piles protected by this process in the Georgia Street wharf at Vallejo, for experimental purposes. These piles were all in actual service under ideal conditions for their use. In about 3 years the battens began swelling away from the pile and borer attack started. The piles are still in service (1925), the borer action being retarded by the surface protection, but it does not appear likely that a life exceeding about 5 years will be secured.

Fig. 38. Bulging battens on piling protected by Moran and Paraffine processes at Georgia St. wharf, Vallejo, after three years' service. (*S. P. Co. Photo.*)

Moran Process

This process was used in 1913 on 50 piles driven by the San Francisco-Oakland Terminal Railways. These were treated similarly to the Paraffine Process piles described above except that Moran's Preservative Compound, made by the Moran Paint & Oil Co. (commercial application for marine construction controlled by the Marine Piling & Preservative Co.), was used and the burlap was omitted, a wire mesh embedded in a heavy coat of the compound being used to hold the coating. Battens were added, however, on account of the rubbing of the piles when rafted. The battens themselves were then protected with a final coating. No satisfactory record of the service secured from these piles is available. Some of them were pulled after five years, sold and redriven in another region of the Bay; but while they are

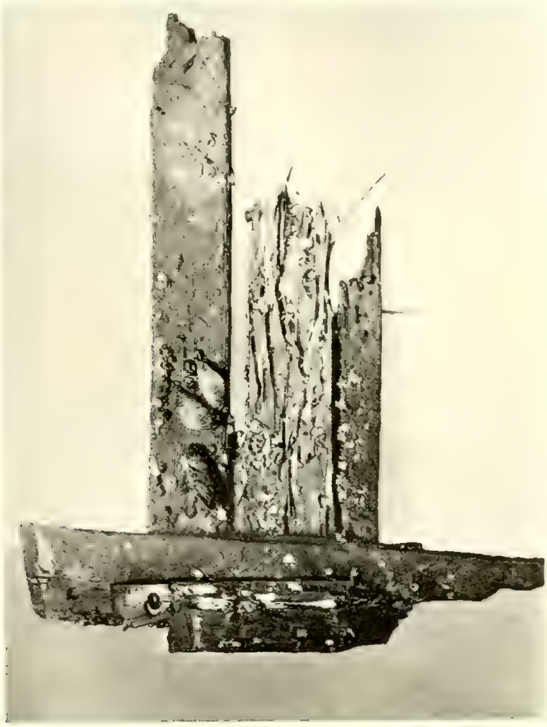

Fig. 39. Battens removed from some of the piles in the wharf shown in figure 38, showing *Teredo* attack in three years. (*S. P. Co. Photo.*)

reported to be still in place, the location of such of them as the Committee could satisfactorily identify is such as to make their performance of little or no value respecting resistance to borer attack.

In 1921 the Southern Pacific Company drove 120 piles protected by this process in the Georgia Street wharf at Vallejo for experimental purposes, along with those of the Paraffine Process mentioned above. In later installations this process has been considerably modified, the changes including the abandonment of the wire mesh because of its rapid corrosion by sea water and the substitution for it of asbestos fibre in the hydrocarbon mixture as a binder, and the substitution of wire wrap for nailing as a medium for holding the battens in place. The same condition has developed with these piles as with the others, the battens having been bulged by bar-

nacles, etc., exposing the pile wood, which is in process of borer attack. A similar life of not more than five years seems probable from current inspections.

Columbia Paint Process

This process as used by the San Francisco-Oakland Terminal Railways in 1913 and 1914 was similar to the Paraffine Paint method, and consisted in applying to the piles a coat of the Harbor Brand Compound, a paint made by the Columbia Paint Co. (now the Columbia Wood & Metal Preservative Co.), a coat of burlap soaked in the paint, redwood battens and a final coat of paint. In addition to such toxic value as it has, the composition made by this company has special usefulness for such purposes as painting application to built-up pile spring line ribbons and submerged bracing. This is due to the fact that the composition forms so cohesive a matrix that boards or planking placed in tight surface contact immediately after receiving a heavy application of the compound can hardly be torn apart, after the compound has set, except with rupture of the wood itself. This adds to the chemical safeguard a mechanical one against the attack of borers in the minute space between built-up members, which is otherwise especially vulnerable.

Argentine Quebracho Process

In 1920 the San Francisco-Oakland Terminal Railways coated 160 piles with about 20 feet of protection consisting of a coat of "Argentine Quebracho Commercial Paint" produced by the Imp Manufacturing Co., then a layer of ½-in. by 2 in. redwood battens and a coat of paint over the battens. The second coat of paint was sanded to harden the surface and prevent the piles from sticking together in the rafts. The same process has also been used by the Six-Minute Ferry Co. at its slip at Crockett. Chemical analysis by the Committee shows no Quebracho in this compound, whose chief constituent appears to be gas tar oil.

Miscellaneous Protective Devices for Wooden Piles

Several methods have been proposed for pile protection which cannot be classified under any of the above heads. The following are examples:

THE BUILT-UP PILE

Much was hoped for this pile at one time. It was a square or rectangular pile built up of separate planks spiked together so as to have, from any direction, the greatest possible number of cracks intercept a path through the pile. This was on the commonly accepted belief that the shipworm would not cross a crack. But whatever the scruples of the shipworm it soon became apparent that *Limnoria* had none. A layer of felt beneath the outside planks helped somewhat; but the spikes in course of a little time loosened and opened the cracks till they offered shelter instead of discouragement to borers. The construction of this type of pile was not continued.

FLOAT PROTECTORS

Floats, loosely fastened around the pile so that they will rise and fall with the tide and keep constantly in motion from wave action have been actively promoted for some years. They are made in various forms. The original idea overlooked the fact that the shipworm borers work mainly below tide levels, and most severely at and near the mud line. Later there were added to the device chain festoons to assist in warding off the borers below the surface tidal range. No record of their commercial use in San Francisco Bay has been found by the Committee, but they have been

installed for a number of years on a pier at Long Beach, Calif. The piles there were attacked by *Limnoria* in scattered spots within a few months. This has been verified by inspection made during the period of this Committee's activity, which also disclosed the fact that a number of the piles upon which the device had been installed were piles which had already been effectively protected from borer attack by creosote treatment. The effectiveness of this scheme is still unproved in water where borer action is known to be severe. The minuteness of the crevices capable of sheltering the almost microscopic borer larvae from any impact from such a device, the relatively long time between tidal passages when any given elevation is not effectively covered by such a device, and the utter inadequacy of chain festoons, or any other pendant device rising and falling with the tide, to protect the submerged portion of the pile, especially that near mud line, where the most severe entrance attack of shipworms occurs, seem on the basis of present knowledge to militate against the success of these devices. Moreover, on the Long Beach pier where they have been longest installed, mechanical wear due to the block ring is materially reducing the effective diameter of the piles between tide levels.

ELECTROLYSIS

Electrolysis of the water around the pile, liberating chlorine, which is supposed to kill the teredos in the pile, has been actively promoted for some years but no record of any commercial installation of the scheme has come to the attention of the Committee. Tests conducted by this Committee and described in the chapter on Chemical Research of this report show, briefly, that chlorine in free sea water maintained for seventy-two hours at a concentration so high as to render the breathing of the air around it difficult, caused no more injury to teredos in infested wood than to suspend their feeding activity while the concentration was maintained. In actual application, moreover, the tidal currents would carry the chlorine away and prevent the borers being subjected to its effects to any great extent. Constant repetition of the treatment would in any case be required to take care of the hordes of larvae arriving with every tide.

DYNAMITING

Dynamiting in the water around the piles has been tried as a means of killing the borers. A concussion of this kind in water will kill animal life only in its immediate vicinity. In any case, constant repetition would be as necessary as in the case of electrolysis.

CREOSOTED WOODEN PILING

Notwithstanding the countless efforts of the past to evolve protections for timber piling, none has thus far been developed to give better general service than the creosoting process—meaning by better service a longer length of life in relation to cost. The creosote process has been successful not only because of the toxic properties of the oil but because of the method of application. The creosote virtually transforms the exposed timber into a material which for a considerable time repels the borers. The protecting shell is an integral part of the pile, homogeneous with it; no plane of separation exists between it and the untreated interior wood, as in the case of protecting armors attached to a pile surface. Therefore none of the normal influences acting on the pile can cause the protecting shell to be forced off or to fall away; where flexibility is required, the shell will act with other portions of the pile and no rupture should develop as in the case of piles built up of heterogeneous parts.

The greatest difficulty in the use of the average surface armor is that of keeping

it intact and firmly attached to the pile. Aside from sleeve pipe protections or concrete shells placed around piles, the armor is usually attached to the wood by means of wire or nails at a comparatively few points. Corrosion weakens these fastenings, various stresses begin to act on the several parts—such as unequal expansion or contraction, wave action, shell fish and mollusc attack in the small crevices—and rupture of the protection soon follows. Sheet metal is easily ruptured and torn away; a pro-

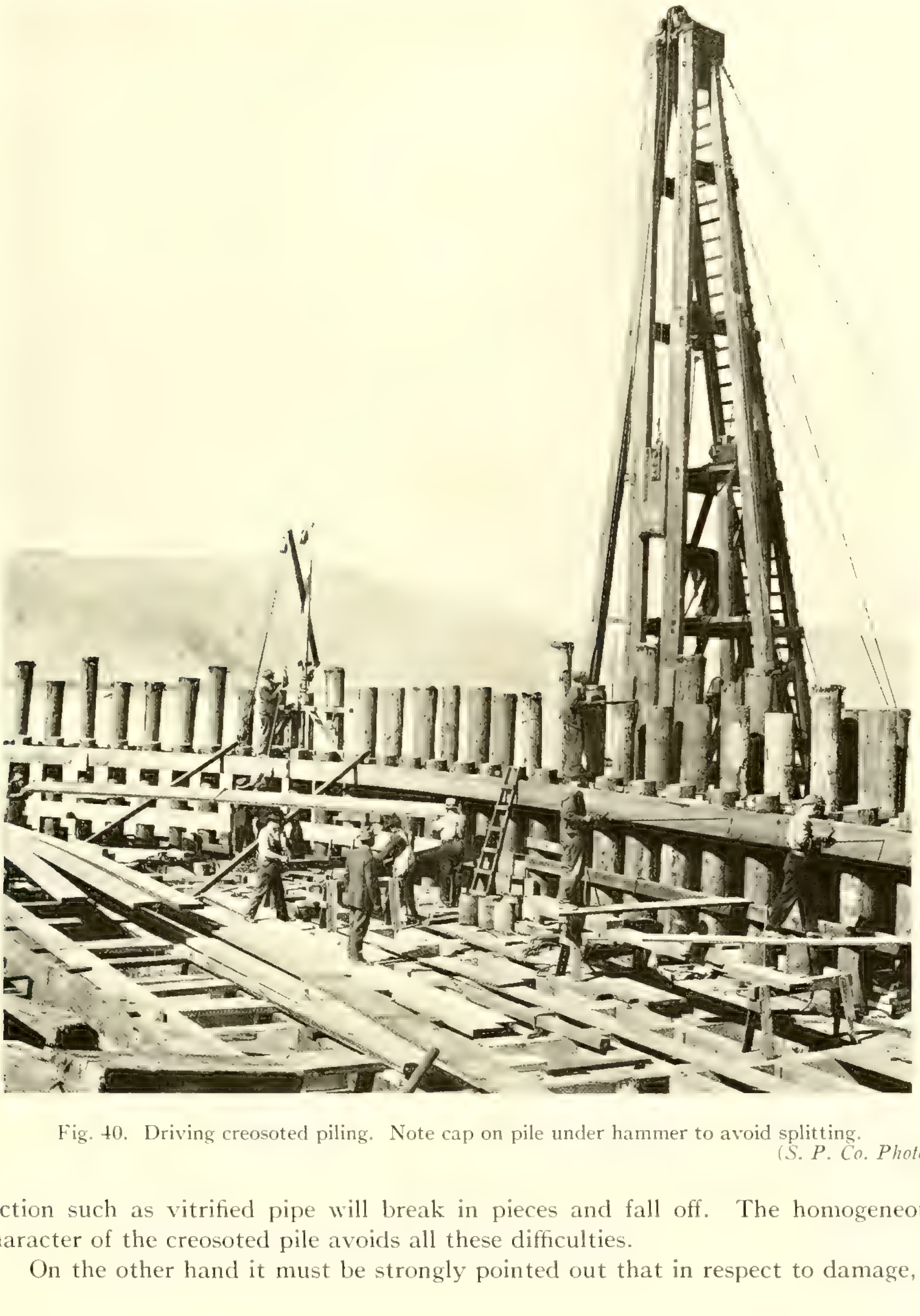

Fig. 40. Driving creosoted piling. Note cap on pile under hammer to avoid splitting.
(S. P. Co. Photo.)

tection such as vitrified pipe will break in pieces and fall off. The homogeneous character of the creosoted pile avoids all these difficulties.

On the other hand it must be strongly pointed out that in respect to damage, if

not mechanically, a creosoted pile is an unhomogeneous structure, the unimpregnated interior being intrinsically no more immune from borer attack than any other untreated wood, and dependent for its protection on the maintenance of the complete integrity of the zone of ½ to 1½ inch thickness of creosote impregnated wood with which it is surrounded. Insofar as the rupture of this zone is easier than would be ideally desirable and as the accepted methods of working with wood provide the temptation to cut and frame and use dogs and pike poles on construction such as this, to its grave injury, creosoted piling may be called a fragile protection and should be treated as should any construction material, with special and intelligent regard to the safeguarding of its particular weak points.

While creosoted piling has been in use continuously for many years, it has not been generally adopted until recently for several reasons: the process is expensive, and the demand for this type of creosoted product has not been large enough that commercial treating plants could be maintained on the local consumption, or could compete in the general field with plants at the source of production of the timber chiefly used for construction purposes. As a result, San Francisco Bay has only one treating plant and that is owned and operated by a railroad for its own requirements only. The difficulty of procuring the piling from distant plants has sometimes led to substitution of other types; sometimes improper treatment and often improper handling have curtailed the effectiveness of the protection and shortened its life, thus causing confidence in it to be lessened. As time has progressed, however, the causes of premature failure have been disclosed, and the consistently good service of piles properly treated and handled has firmly demonstrated the high value of the process.

Treatment of Douglas Fir Piling

Douglas fir is very refractory to the penetration of preservatives in the heartwood. The sapwood is less refractory, but it is difficult to obtain an absorption in Douglas fir piling of much over 12 to 14 pounds per cu. ft. of treated material. The thickness of the sapwood is the ultimately limiting factor in the depth of the penetration that can be secured.

The piles driven in Oakland Long Wharf in 1890 and 1892, totaling about 1000, were air-dried for a year before treatment, then treated by the Bethel process, absorbing about 14.2 lbs. per cu. ft. The other 13,000 piles in this structure were treated green from the water, by the boiling process as developed by John D. Isaacs, and received an average absorption of about 10 pounds per cu. ft. Since that time piles have been used in the bay treated by the steaming process, the boiling process and the boiling under vacuum process. All three processes are still used but the present tendency seems to favor that of boiling under vacuum. (See specifications for creosoted piling and timber for use in marine structures, beginning on page 108.)

The Spliced Creosote-Greenwood Pile

Some creosoted piling has been used in San Francisco Bay, to the small or bottom end of which is spliced an untreated piece somewhat shorter than the length which will be driven below the mud line. This device permits the purchase of much shorter creosoted piling, which is also cheaper per linear foot than material of longer and larger dimensions. It may give satisfactory service, if the splice is sufficiently strong, subject to precautions against the exposure of untreated wood by miscalculation of driving length, or by subsequent scouring of the bottom. The late Mr. Howard Holmes, of San Francisco, used successfully a metal sleeve of several feet length

over the splice. Whether the spliced pile would be economical would depend upon the relation between splicing cost and the saving in creosoted material.

Life of Creosoted Piling

Respecting the average life possible for creosoted piling, all estimates exceed those for other forms of chemical protection under comparable conditions. Mr. G. F. Nicholson, Los Angeles Harbor Engineer, places the life at from 20 to 30 years in San Pedro Bay; the extensive service records accumulated by this Committee place the life in San Francisco Bay at from 15 to 25 years on the San Francisco side and from 20 to 30 years elsewhere in the Bay. It is likely that a similar range of from 15 to 30 years' life could be secured in all Pacific Coast harbors, the actual point attained being dependent, as it is here, partly on the severity of borer attack, but chiefly on the intelligence and care used to protect the integrity of the creosoted shell, throughout the whole course of the piling from the creosoting plant to its place in the structure, and thereafter in preventing "pike pole inspections." In this connection the fact, previously discussed in this report, is especially important that, as shown by a recent thorough-going repair survey of nearly the whole San Francisco waterfront, by the Board of State Harbor Commissioners, 80 per cent of all holes in the treated shell of creosoted piles through which borer entrance had been gained and attack started were caused by dogging the piles, without subsequently plugging the holes. These points of handling and construction practice, so necessary to the use of creosoted construction materials with results of maximum effectiveness, are discussed in detail at page 73 of the Marine Structures chapter.

COMMITTEE SPECIFICATIONS COVERING CREOSOTED DOUGLAS FIR PILING AND LUMBER FOR USE IN MARINE STRUCTURES

Prepared by F. D. Mattos *and* R. H. Rawson
Adopted by the Committee 1921, Revised 1924

MATERIALS TO BE TREATED

Green and Water Stored Piling

QUALITY

Piles shall be cut from sound trees; shall be close grained and solid, free from defects, such as injurious ring shakes, large and unsound or loose knots, decay or other defects which in the opinion of the inspector may materially impair their strength or durability.

STRAIGHTNESS

Piles shall have a uniform taper and none with swell or twisted butts will be accepted. Piling shall be so straight that a straight line drawn from butt to tip will not deviate more than one (1) inch for each ten (10) feet in length; that is to say, piling seventy (70) feet in length may deviate seven (7) inches from a straight line drawn from butt to tip. Piling with short or reverse bends, or kinks, will not be accepted.

TWISTS

No piling with spiral grain will be accepted which has one complete twist in a length of forty (40) feet or less.

TRIMMING

Piling shall have all bark and inner skin removed. Knots shall be cut flush, butts and tips trimmed squarely before treatment, and in case piling has been stored in sea water, barnacles or similar forms of sea life shall be removed. Piling showing any attack of insects or marine borers will not be accepted.

SAPWOOD REQUIREMENTS

Only such piling shall be accepted for treatment as conforms with the following minimum sapwood requirements:

1. For a specified absorption ranging from twelve (12) pounds to fourteen (14) pounds of creosote oil per cubic foot of timber, the sapwood shall not be less than one (1) inch in depth.

2. For a specified absorption of sixteen (16) pounds of creosote oil per cubic foot of timber, the sapwood shall not be less than one and one-quarter ($1\frac{1}{4}$) inches in depth.

EXCEPT THAT

3. Piling which does not meet the sapwood requirements specified above will be accepted, provided that the creosoting company will in each case guarantee the minimum penetration of creosote oil specified.

SIZES

Shall be as specified by the purchaser. For information, the following appropriate size combinations of length and of butt and top diameters are listed by groups, of

which the group to be selected will depend upon the class of structure desired and the load for which it is designed:

GROUP "A"

Lengths	Minimum Diameter Butts	Minimum Diameter Tips
Up to 49′ inclusive	12″	8″
50′ to 64′ inclusive	13″	8″
65′ to 74′ inclusive	14″	8″
75′ to 100′ inclusive	15″	7″
101′ and up	16″	7″

GROUP "B"

Lengths	Minimum Diameter Butts	Minimum Diameter Tips
Up to 60′ inclusive	14″	9″
61′ to 80′ inclusive	15″	8″
81′ to 100′ inclusive	16″	8″
101′ and up	17″	7″

No piling with butt diameter greater than twenty-two (22) inches will be accepted unless otherwise stipulated. In determining the diameter of a pile not having a circular cross section, the average of the minimum and maximum measurements at that cross section shall be taken.

Air Seasoned Piling

Piling stored on land and air seasoned shall in all particulars meet the foregoing specifications for green, freshly cut and water stored piling. Piling stored on land for air seasoning must be piled on skids or other supports such as to keep the piling at least ten (10) inches above the ground, and each layer of piling shall be separated from the others by strips not less than three (3) inches in thickness, in order to permit a free circulation of air. Piling stored in this manner will be considered thoroughly air seasoned when its moisture content, based on the oven dry weight, has been reduced to twenty (20) per cent.

Air seasoned piling with checks of such size as will impair the strength and durability of the piling will not be accepted, regardless of the fact that such checking has taken place naturally.

Sawed Lumber and Timber

QUALITY AND GRADE

The purchaser shall specify commercial grade desired according to Grading Rules standard or currently recognized in the production and marketing of the species of timber or lumber involved; the material so to grade after treatment. The standard commercial grade usually specified for creosoting purposes is that known as Select Common Douglas fir, in accordance with Domestic List No. 7, edition of 1917, published by the Pacific Lumber Inspection Bureau, Inc. The American Lumber Standards, recently formulated by the industry in cooperation with the Government, will doubtless govern in the future. The American Standard grade nearest equivalent to the former select common is designated No. 1 Common.

PREPARATION FOR TREATMENT

Selecting Material for Loading Cylinder Charges

SAWED LUMBER AND TIMBER

Care must be taken to secure material of approximately the same moisture content for the same cylinder charge; that is, green or freshly cut lumber and timber must not be mixed with seasoned or partially seasoned material.

PILING

As in the case of sawed lumber and timber, all piling to be treated in the same cylinder charge shall be approximately of the same moisture content. In loading piling for cylinder charges the following classes of material shall be treated, each by itself:

1. Green or freshly cut piling.
2. Piling water stored for thirty (30) days or more.
3. Partially air seasoned piling.
4. Thoroughly air seasoned piling.

Any further separation or segregation of material shall be optional with the creosoting company.

Inspection of Material Before Treatment

Before the material is loaded on tram cars for treatment the inspector shall be given full opportunity to examine it and to check the cubiture records of the plant for each cylinder charge, and these records shall be open for his inspection at all times.

Thermometers and Gauges

All the treating cylinders of the creosoting company which are used on work covered by this specification shall be provided with the following accurate instruments:

1. Recording Thermometers.
2. Recording Pressure Gauges.
3. Recording Vacuum Gauges, or combination recording pressure and vacuum gauges.
4. Indicating Mercurial Thermometers as a check against the Recording Thermometers.
5. The creosoting company shall also provide accurate maximum reading thermometers for use by the inspector from time to time in checking the recording and indicating thermometers.

The inspector must check the recording and indicating thermometers at frequent intervals. This may be done by placing a maximum reading thermometer at some point on the charge which will bring it as near as possible to the thermometer which is to be checked. When the charge is removed from the treating cylinder after treatment the maximum reading shall be read and this reading checked against the maximum temperatures recorded by the cylinder thermometers. Should there be a variation greater than five (5) degrees Fahr. in the readings of the instruments, necessary adjustments must be made.

CREOSOTE OIL

The oil shall be a distillate of coal-gas or coke-oven tar. It shall comply with the following requirements:

1. It shall not contain more than 3% water.
2. It shall not contain more than 0.5% of matter insoluble in benzol.
3. The specific gravity of the oil at 38° C. compared with water at 15.5° C. shall be not less than 1.04.
4. The oil shall contain from 5 to 10% tar acids.

5. The distillate, based on water-free oil, shall be within the following limits (test to be made at, or corrected to atmospheric pressure at sea level):

   Up to 210° C. not more than 5%.
   Up to 235° C. not more than 25%.
   Up to 315° C. not less than 45% nor more than 75%.
   Up to 355° C. not less than 70% nor more than 90%.

6. The residue above 355° C. shall have a float-test of not more than 50 seconds at 70° C.
7. The oil shall yield not more than 2% coke residue.
8. The foregoing tests shall be made in accordance with the standard methods of the American Railway Engineering Association.

TREATMENT AND INSPECTION

Treatment shall be by the Boulton process (boiling under vacuum).

Treatment of Green or Freshly Cut, Water Stored and Partially Air Seasoned Piling

PERIOD OF ARTIFICIAL SEASONING

After the piling is placed in the treating cylinder, it shall be immersed in creosote oil and kept covered during the entire boiling period of the process, the oil level being at least four (4) inches above the topmost pile.

After filling the treating cylinder with creosote oil as above specified, connections between condenser and vapor drum on treating cylinder shall be opened, steam shall then be admitted through the heating coils and shall be so regulated that the temperature inside the treating cylinder is kept rising as fast as the condensation will permit, until a temperature of 215° F. is reached. Having reached this temperature, a vacuum of at least twenty (20) inches of mercury shall be produced and maintained in the treating cylinder, the escaping vapors being drawn into the condenser. This operation shall be continued until such time as the amount of condensation collected in the hot well of the condenser does not exceed one-tenth (0.1) of a pound of water per cubic foot of timber in charge per hour, at a temperature not to exceed 220° F. inside the treating cylinder. This temperature shall be regarded as the absolute maximum to be allowed.

PRESSURE PERIOD

After the period of artificial seasoning has been completed, as specified in the foregoing, the temperature inside the treating cylinder shall be allowed to drop to approximately 200° F. The treating cylinder shall then be completely filled with hot creosote oil (temperature about 170° F.) from the operating tank, after which all vents shall be closed and more oil pumped or forced into the treating cylinder from the operating tank until the pressure gauge on the treating cylinder records a five (5) pound pressure (this to insure that the cylinder is full). Creosote oil from a measuring tank shall then be forced into the cylinder at a pressure not to exceed 175 pounds per square inch. This operation shall be continued until such time as the piling has absorbed sufficient oil to insure the final retention of the amount specified after the treating cylinder has been drained. This having been accomplished, the piling may be removed from the treating cylinder as soon as the temperature within the cylinder has dropped below 200° F. The application of a final vacuum for a period not to exceed one hour will be allowed to recover drip.

Treatment of Air Seasoned Piling

In the treatment of air seasoned piling, where artificial seasoning is unnecessary, the piling may be held in hot oil at a temperature of 180° to 190° F., until such time as it has been heated sufficiently to permit impregnation without the use of excessive pressures. This having been accomplished, the required amount of creosote oil may then be injected as in the foregoing case of green or water stored piling, and upon being removed from the treating cylinder, under similar conditions, this piling shall stand the same detailed inspection.

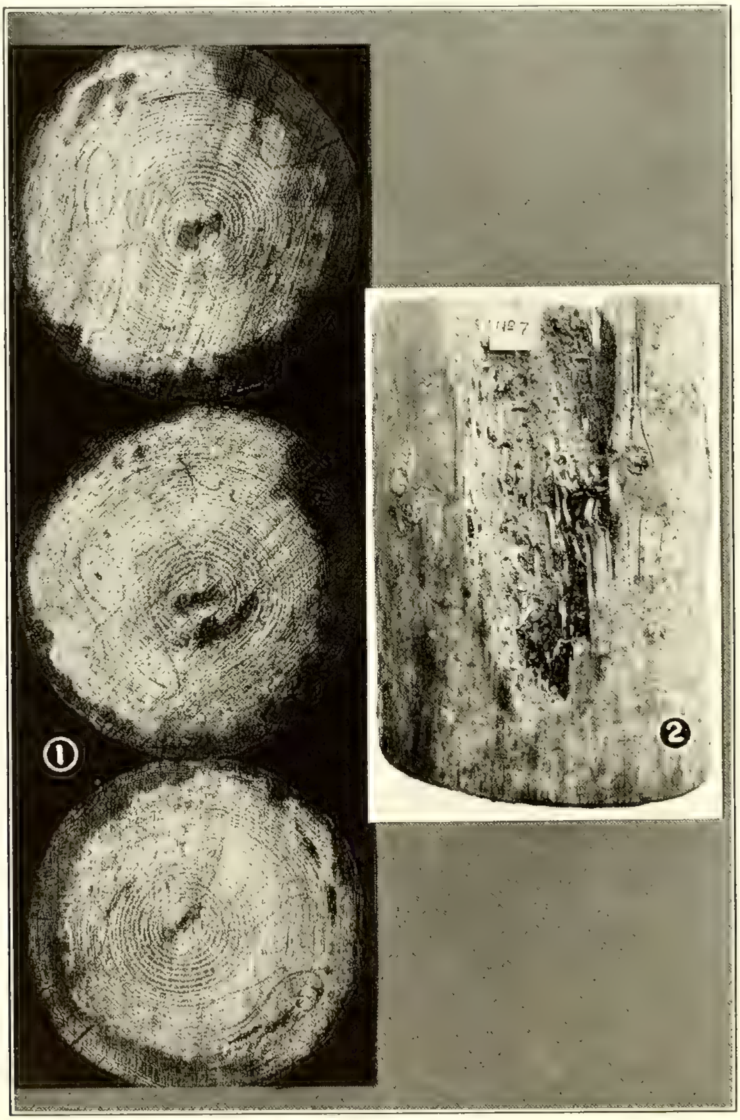

Fig. 41. (1) Section of new creosoted piles delivered on San Francisco Bay, 1921, showing uneven penetration of creosote.
(2) Attack on pile by *Limnoria* and *Bankia*, made possible by thin creosote penetration.

Inspection of Treated Piling

PHYSICAL CONDITION

After the piling has been removed from the treating cylinder and allowed to cool in the air for not less than six (6) hours, it must be free from all heat checks, water bursts, and other defects due to improper treatment, which would, in the opinion of the inspector, impair its usefulness or durability for the purpose intended.

NET ABSORPTION

Shall be as specified by the purchaser.

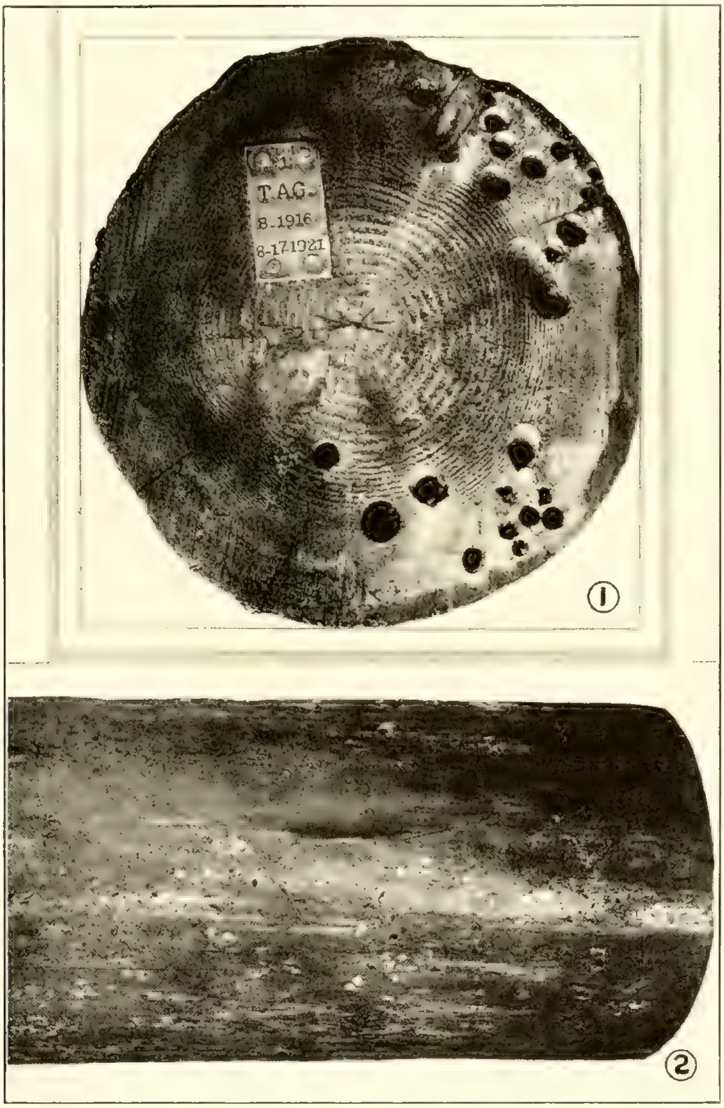

Fig. 42. (1) Cross-section of piling showing thin treatment through which *Bankia* penetrated to interior of pile.
(2) Surface of same pile as in (1), showing entrance holes of *Bankia*.

PENETRATION

Piling shall be accepted upon the showing of penetration of creosote oil in each pile. This penetration must be based on black or very dark oil and in no case will a light discoloration of the wood due to treatment be taken into consideration in measuring the depth of penetration upon which the piling is to be accepted.

The test for penetration shall be made by boring the piling midway between ends with either an increment borer, or a five-eighths (⅝) inch auger, the choice of which shall be optional with the inspector. Each hole so bored shall be plugged with a tight-fitting creosoted plug furnished by the creosoting company. Should the inspector, upon boring the piling, find that the borings contain free moisture, he shall reject any such piling and have same retreated under the conditions hereinbefore specified. The inspector must in all cases bore every pile in the charge for penetration and at least six (6) of these piles must be bored from two different angles in order that he may satisfy himself that the piling has the minimum specified penetration on all sides.

The minimum depth of penetration with specified amounts of creosote oil shall be as follows:

12 pounds of oil per cubic foot— ¾″ penetration.
14 pounds of oil per cubic foot— ⅞″ penetration.
16 pounds of oil per cubic foot—1 ″ penetration.

The curves shown on fig. 43 are given for information and show the theoretical relationship between the amount of creosote oil injected per cubic foot and the average depth of penetration in inches.

Treatment of Green or Freshly Sawed Lumber and Timber

As hereinbefore specified, this material must be treated separately and must not, under any circumstances, be loaded with partially seasoned or thoroughly air seasoned material for the same cylinder charge. In loading sawed lumber and timber on tram cars for treatment, stickers or separators must be placed between all the layers as the material is placed on the tram car, in order to insure complete access of the creosote oil to all surfaces of the wood.

The process of treatment shall be identical with that specified for green or water stored piling, with the exception that the minimum and absolute maximum temperatures will be 180° F. and 190° F. respectively. This temperature shall be maintained constantly under a vacuum of at least twenty (20) inches mercury during the period of artificial seasoning, until such time as the water accumulating in the hot well of the condenser does not exceed one-tenth (1/10) of a pound of water per cubic foot of timber in charge, per hour.

Treatment of Air Seasoned Sawed Material

This material, as in the case of green or freshly sawed lumber and timber, shall be treated separately and in no case shall it be mixed with and treated in the same cylinder charge with other material of different moisture content. In this case the period of artificial seasoning may be dispensed with, but the material may be held in hot oil at a temperature of 180° F. to 190° F. until it is heated sufficiently to permit proper treatment. This having been accomplished, pressure may be applied until the required absorption has been reached.

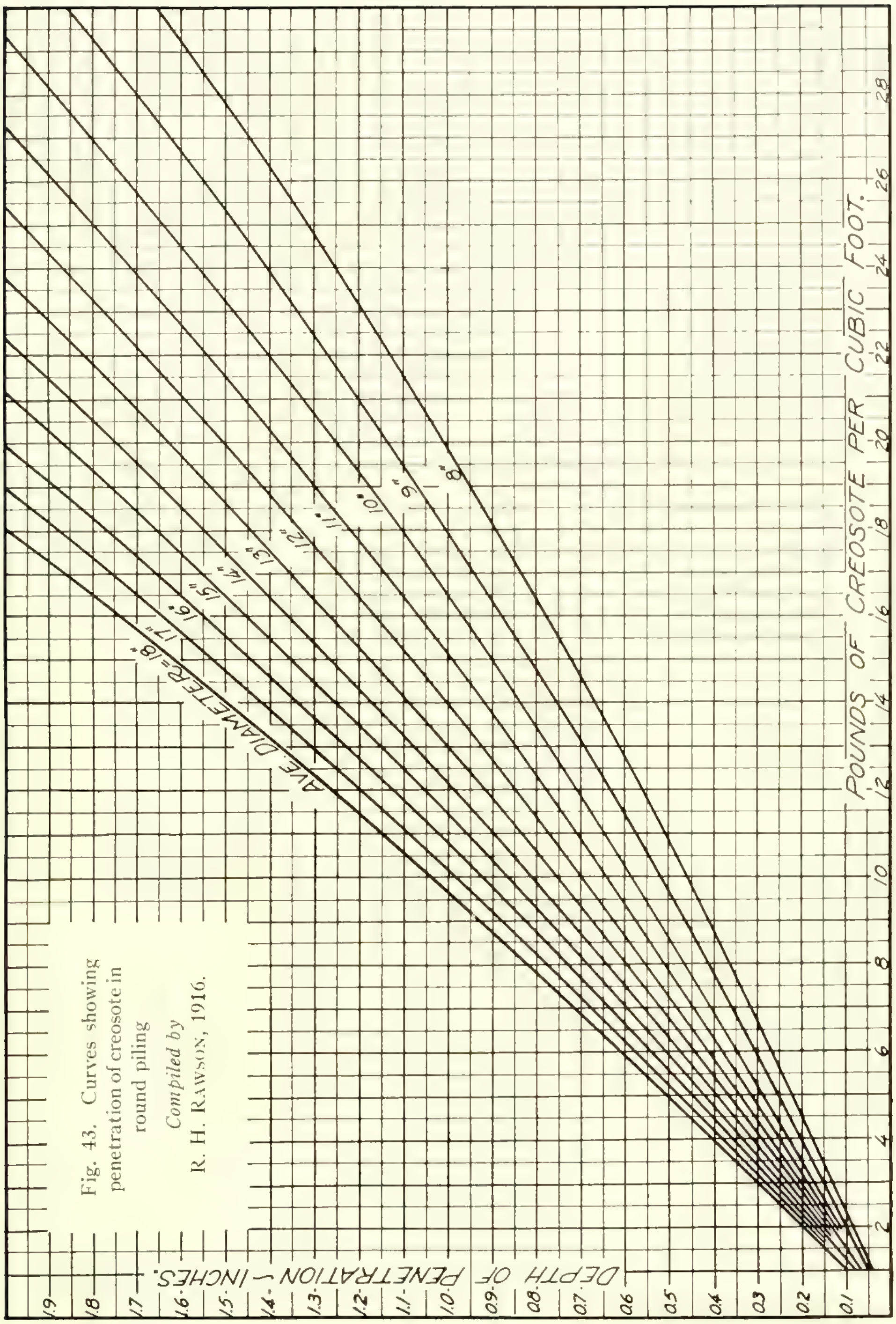

Fig. 43. Curves showing penetration of creosote in round piling

Compiled by
R. H. Rawson, 1916.

Rueping or Empty Cell Treatment

In no case is the Rueping or Empty Cell treatment recommended for piling, regardless of its intended use, or for sawed lumber and timber to be exposed to the action of marine borers.

If sawed lumber and timber are to be treated for uses other than those mentioned above, and empty cell treatment is desired, the following procedure is recommended:

Following the warming up period in the case of air seasoned material, or the seasoning period in the case of freshly cut or green material, as previously described, and as soon as the treating cylinder has been completely drained, the timber shall be subjected to an air pressure of sufficient intensity and duration to provide for the injection of the preservative necessary to secure the specified final retention of preservative. The preservative shall then be introduced, the air pressure being maintained constant until the cylinder is filled. The pressure on the preservative shall then be gradually raised until it is not less than one hundred (100) pounds per square inch greater than the air pressure at which the treating cylinder was refilled. This pressure must be held until sufficient preservative has been introduced to insure the specified final retention after the final vacuum has been applied.

Pressures in excess of two hundred (200) pounds per square inch will not be permitted. The temperature of the preservative during the pressure period shall be not less than 170° F. nor more than 190° F. Upon completion of the pressure period, the treating cylinder shall be speedily emptied of preservative and a vacuum of not less than twenty-two (22) inches promptly created and maintained for a period not to exceed two (2) hours; this in order that the material may be removed from the treating cylinder free from dripping preservative.

Inspection of Treated Sawed Material

PHYSICAL CONDITION

After the material has been removed from the treating cylinder and allowed to cool in the air for not less than six (6) hours, it shall be free from excessive checking, water bursts, warping, shrinkage, or any other defects due to improper treatment and which, in the opinion of the inspector, would impair its strength and durability for the purpose intended.

NET ABSORPTION

Shall be as specified by the purchaser. Final retention shall be determined by weighing sufficient representative material before and after treatment and making necessary corrections for loss in its moisture content.

PENETRATION

The treated material shall be accepted upon the showing of black or very dark oil penetration, slight discoloration of the wood due to treatment not being considered in determining penetration. If, upon boring the material, it is found that the borings contain free moisture, the inspector shall reject any such material and have the same retreated. The acceptance of lumber shall be based on the penetration shown by boring at least twenty-five (25) per cent of the lumber in each charge. The penetration for any given absorption shall be based on the surface area exposed. The theoretical depth to be obtained with a specified amount of creosote oil is shown for information on the curves for various sizes of lumber and timber, in fig. 44.

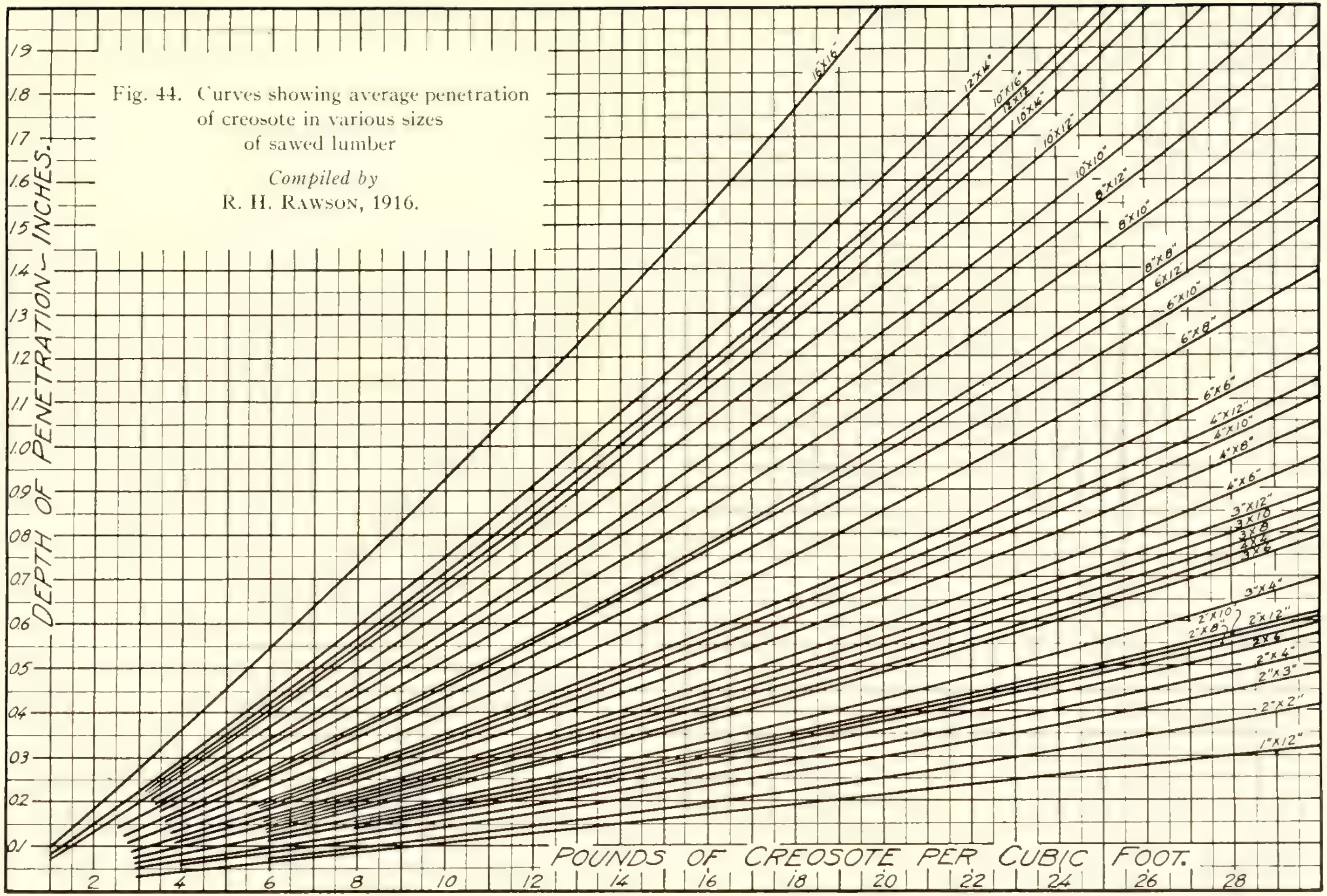

Fig. 44. Curves showing average penetration of creosote in various sizes of sawed lumber

Compiled by
R. H. Rawson, 1916.

HANDLING AND CARE OF TREATED MATERIALS

No treated piling, lumber or timber will be accepted that has been injured during treatment by rubbing or scraping against tram arms or rivet heads, or by rough handling.

In handling treated material extreme care must be used not to damage the edges of lumber and timbers, or to break through the portions penetrated by the preservative and thus expose untreated wood. Sharp pointed tools, such as cant hooks, peavies, pickaroons and crowbars, must not be used except in the ends of treated sawed material and in the ends, or within three (3) feet from the ends, of creosoted piling.

In the rafting of creosoted piling, the use of dogs will only be permitted, provided the dogs are driven within three (3) feet of either end of the pile. Should the creosoting company place these dogs farther from the ends than above specified, the piling may be rejected. All dog holes must be plugged with creosoted plugs.

No treated material carried in stock by the creosoting company can be applied on the purchaser's contract without the consent of the purchaser. If agreeable to the purchaser to apply stock materials on his contract, such material must stand the same rigid inspection as hereinbefore specified for the various classes of material.

GENERAL CONDITIONS OF CONTRACT

1. The Creosoting Company shall furnish an affidavit giving a description of the material furnished—if lumber, the grade, treatment and tally of same; if piling, the butt and tip measurements, lengths and treatment. In all cases they must furnish an analysis of the creosote oil with which the material was treated. When material is purchased subject to tally and inspection by the creosoting plant, such inspection by the plant, as evidenced by sworn certificate, shall be final.

2. An inspector may be appointed by the purchaser to make such inspection at the creosoting plant as will enable him to accept such material, before and after treatment, as meets the requirements of this specification.

3. All facilities and reasonable assistance which the inspector may need to execute his work shall be given by the creosoting company free of cost to the purchaser.

4. The creosoting company shall supply the inspector with such samples of creosote oil as he may direct. The samples thus taken shall be sent to the purchaser for analysis unless the inspector is qualified by both training and experience to make these analyses and the purchaser authorizes him in writing to conduct such analyses at the plant. In this case the creosoting company shall provide the inspector with the necessary chemicals and laboratory equipment for carrying on this phase of the inspection.

5. The inspector shall have access to all parts of the plant which have to do with the treatment of material under his charge.

6. The fact that the purchaser has an inspector at the plant shall not relieve the creosoting company of the responsibility of seeing that the treatment of all material is properly done, and that the agreed penetration of oil is secured in each case as specified for the contract absorption.

CONCRETE

The use of concrete in marine substructures is a comparatively recent development. When first adopted for this purpose it was popularly believed that concrete could be placed in seawater indiscriminately and become as permanent as natural stone. The subsequent period witnessed many costly failures. When not understood,

these failures caused the material as a whole to fall into disrepute, as has been the case with many other good materials. The use of concrete has persisted however and sufficient time has elapsed to disclose the reasons for failures and the means by which most of them may be avoided and successful results obtained.

COMBINATIONS OF CONCRETE AND TIMBER

Combinations of these two materials have been used in a wide range of types, from those in which timber supporting units are protected by concrete shells to those in which concrete supporting units are superimposed on timber pile foundations. The former, from the standpoint of concrete itself, is a secondary use, the latter falling with the use of concrete as a primary construction material. When used as a protection for timber the concrete may be applied either during initial construction or as a repair protection to existing timber.

The substructure uses of concrete, of both the above classes, may farther be divided into those cast-in-place and those pre-cast.

The cast-in-place types all involve the common procedure of placing a form and depositing the concrete in place in the structure. The types differ in the details of form material and construction and in the method of depositing the concrete. Good results are possible if the forms are tight so that salt water and mud can be excluded from the concrete while it is being placed. This usually involves driving or sinking the form into the substrata, pumping out the mud and water, and sealing the bottom, unless the substrata are sufficiently solid that the form will remain empty without it. As the depth of water increases it becomes increasingly difficult to obtain sound concrete and, in pile jackets, even thickness and good reinforcement in so thin a shell.

The pre-cast types involve units completely constructed on shore and subsequently placed in the structure. The great advantage of this method is that the unit can be carefully constructed and a good quality of concrete obtained, a condition which is difficult to secure when the work is done in place in water. Pre-cast types include the timber pile protections in which a pre-cast reinforced concrete sleeve or jacket is slipped over the pile after it has been driven, and those in which the concrete or cement cover is fabricated on the pile before driving; pre-cast "socket" columns in which a concrete column is cast with a long socket at its lower end such that it can be slipped over a single timber pile cut off near the mud line: large pre-cast reinforced concrete caissons, either bearing directly on hardpan or enclosing a pile cluster, which are ultimately filled solid with concrete; and pre-cast reinforced concrete piles.

Concrete Protections for Wooden Piles

Inasmuch as this use of concrete forms is in reality a phase of the external protections for wooden piling, which have already been discussed for other materials than concrete, its discussion will here be undertaken before that of the use of concrete as a primary construction material, with the understanding that the considerations in respect to fabrication of the concrete and its pouring, setting, protection from deterioration, etc., to be presented in the discussion of the latter apply in general with equal force to the pile protection form of concrete construction.

PROTECTIONS CAST IN PLACE

There are several different methods, which are quite distinct from each other.

The Stationary Form Type

Placing full-length, stationary forms around piling and filling the forms with concrete has been tried many times, usually as a protection for piling in place which

is being attacked. The details of the forms, reinforcement and methods vary considerably. The forms are usually left permanently in place.

The Culvert Pipe Method

This form of construction has been used at two places on San Francisco Bay and is reported to have been used recently at two places on the Oregon coast. It consists of slipping a corrugated iron culvert pipe over the end of the pile, forcing the former as deeply as practicable into the sand or mud and filling the space between the pipe and the pile with concrete. This method has not been used recently in this region, and the Committee has not learned just how the work was done on the Oregon coast. Other cylinder forms, as well as ordinary box forms, have been used in this type of process. Reinforcement, if used, may be in the form of rods, wire mesh or spikes driven into the pile, or it is sometimes omitted altogether. No data are yet available on the cost of this process, or the durability of the pipe and concrete.

The effectiveness of the method will depend upon the life of the casing, the quality of the concrete and the success in getting the protection deep enough into the bottom to avoid danger from a changing mud line. This method is entirely feasible where the mud is exposed at low tide and where, on account of the relative shortness of the protection and the fact that the mud is exposed at low water, the workmen can see their work and it should be possible to obtain good concrete. The necessity of working between tides, however, requires considerable speed, with the accompanying danger of sacrificing quality. When the protection is thus exposed at low tide, it is also an easy matter to inspect it and to keep it in good repair. The deeper the water, the less practicable the method becomes because of the increasing difficulty already mentioned of making the forms watertight and thus avoiding the uncertain quality of concrete formed by dropping it through water, of obtaining such a relatively thin shell of satisfactorily even thickness, and of securing proper reinforcement of this shell. Thorough inspection is also rendered more difficult. The specific installations of this general type, of which the Committee has record, are as follows:

The city of Alameda in 1914 built a pipe line trestle about 1400 feet long, consisting of two-pile bents spaced 15 feet apart. The piling used for the initial construction was Douglas fir, protected by a coating of asphaltic tar, burlap and redwood battens. After a short time this protection proved ineffective against the attack of *Limnoria*, and it was decided to encase the piles in concrete. Metal forms were placed at low tide, the concrete poured and the forms subsequently removed. The cost of this work is reported to have been $4,000, with labor at $2.50 per day. This amounted to an average cost of about $22 per pile. In December, 1920, the piles were examined, at a time when about half of them were exposed down to the mud line. The concrete on eight was found to be disintegrating. Untreated wood at the bottoms of four was being exposed to borer attack; and the covering had not been placed high enough in six cases, so that *Limnoria* was working above it.

In March, 1919, the U. S. Naval Training Station repaired 20 damaged piles at Yerba Buena Island, 16 ins. in diameter by placing No. 16 gauge galvanized iron forms 30 ins. in diameter around them and filling with concrete. The concrete was reinforced by No. 10 gauge 4-in. wire mesh secured to the wood and held 2 inches from it by No. 40 spikes. The average cost, including labor and material, was $2.00 per lineal foot. Insufficient time has elapsed to indicate the effectiveness of this protection.

Pile-Cluster Concrete Cylinders with Permanent Steel Forms

This type of substructure support is formed by driving a cluster of timber piles; a steel cylinder form is then lowered over the cluster and driven into the mud; the form is then pumped dry and filled with concrete, completely encasing the piles.

This type, using 3-pile clusters, was introduced at San Francisco in 1895-96, when 130 were used in constructing Pier No. 5 (Old Pier No. 7—Pacific St. Wharf), and 120 in Pier No. 20 (Old Pier No. 12—Folsom St. No. 1). The steel forms were made of $\frac{3}{16}$ in. boiler plate, were 4 ft. in diameter and averaged 45 ft. in length. Old wire cable was used as reinforcement for the concrete. The cost of Pier No. 5 (exclusive of the shed) was about $48,000 or $0.80 per sq. ft. It was reported at the time that the steel cylinder forms cost $4.50 per lin. ft. Most of these units are still in service after 29-30 years, having had the longest life of any substructure supports on the San Francisco waterfront, although a number have been replaced due to the failure of both the steel shell and the concrete, and while in some which remain the concrete has disintegrated but is protected by the steel form.

Holmes Concrete Cylinder Piers

The so-called Holmes cylinders developed by Mr. H. C. Holmes, former Chief Engineer of the Board of Harbor Commissioners, were modifications of the 3-pile cylinders used in Piers 5 to 20 described above, timber forms being used, for reasons of economy, instead of steel. The forms were built of 2-in. and 3-in. wood staves bound with steel hoops. Those for single piles were about 2 ft. in diameter, and for 3-pile clusters from 3 ft. 6 in. to 4 ft. 10 in. The sequence of construction was to drive the piles, lower the form into position, pump out the mud and water, place the reinforcing bars, and pour the concrete. The forms were left in position and were eventually destroyed by borers.

These cylinders built with 3 piles were first introduced in the Howard St. Wharf No. 3 (Old Pier No. 10) in 1900. During the next six years several wharves were built with the 3-pile type aggregating a total of about 3,000 cylinders.

In the next few years some of the cylinders failed and fell from position. By 1915 their condition had become such that the majority were removed or replaced. Pier 10, mentioned above, was completely removed in 1915. The life of the majority ranged from 7 to 15 years—a few are still in place after 25 years' service.

In reviewing causes of these unsuccessful results it appears that the original intention to pump the forms dry before placing concrete could not be carried out in actual construction. It was found impossible to prevent leakage of the forms and to seal the bottoms, bags of cement placed at the bottom in an effort to accomplish the latter being only partially effective. As a result, much of the concrete was placed, or went through its setting process, in water.

Subsequent investigation indicated the following causes of failure: (1) Poor concrete because of setting in salt water; (2) mud and sand pockets due to failure to seal the bottom; (3) pockets formed by arching of concrete due to faulty workmanship; (4) laitance pockets and joints due to excess water and to failure to pour each unit completely without stopping; (5) failure to carry cylinder concrete down far enough into the mud to allow for scouring; (6) failure to place adequate reinforcement to prevent separation of parts when ruptures of concrete occurred.

These construction difficulties led to the abandonment of the 3-pile type. Mr. Holmes later developed a single-pile unit used in the construction of Pier 34 in 1910. The forms for this reduced size were easier to handle and could be kept more nearly

watertight. A special gasket was placed around the pile at the bottom of the form which sealed the latter and excluded the mud and water. This type, where thus well constructed, has given excellent service. A recent inspection of Pier 34 disclosed only minor flaws which were readily repaired.

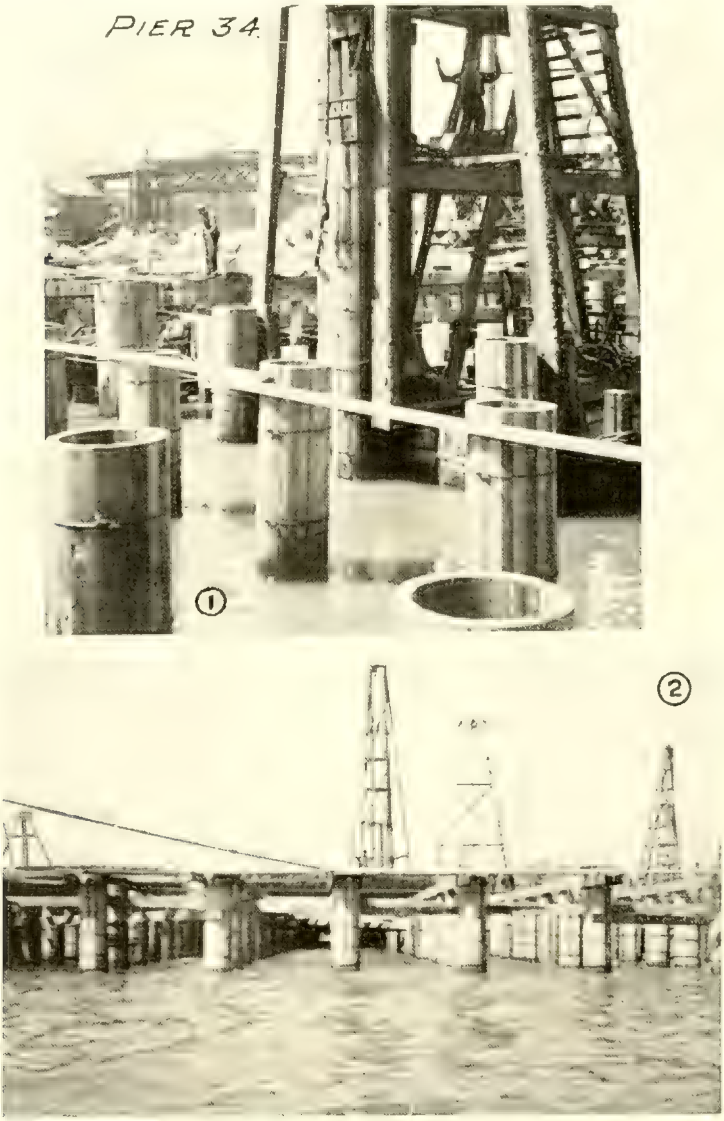

Fig. 45. (1) Holmes wooden stave cylinders being driven at Pier 34, San Francisco.
(2) Outer end of Pier 34, San Francisco, during construction, showing Holmes cylinders.
(*Photo by Mr. Howard C. Holmes.*)

The Removable or Sectional Form Type

Methods of placing concrete in removable forms around a pile in place have been in use for several years. The sections are short, especially adapting them to the conditions of limited working space between water surface and the under side of the wharf floor, and permits such work to be carried out without the necessity of removing the floor or superstructure. Their chief application is to the salvaging of piles in place

and already attacked by borers, for which they afford the only practical means which has come to the knowledge of the Committee. The forerunner of the present systems was one of them. The one most used in the San Francisco Bay district is that employed by Mr. Frank Camp. Mr. Alois Neubert, a diver and piling repair and construction contractor of long experience, has also an interesting process.

Black's Patent

This was the forerunner of the present day sectional form pile jacket construction. It was used from 1908 to 1913, the most important installation being of some 2000 in large docks of the Standard Oil Company at Richmond. The concrete was poured above water level in successively added sectional forms, as in the present day methods; but the forms were of metal, each successive section being secured to the preceding as it was added, and the forms were left in place after the operation was completed. The method was thus much slower, less convenient and less adaptable than the later modifications with hinged wooden quarter sections, and suffered from at least as many shortcomings. The results were not on the whole promising. The Richmond installation gave good service, but more than one-half of them were used over copper sheathed piles beginning to show need of additional protection. Out of 300 installed under normal conditions, for the State Harbor Commission, over 80 per cent have been removed. The method is no longer actively promoted.

Camp Process

This process of timber pile protection is perhaps the most typical method. It consists in placing the concrete jacket in forms made in 3-ft. cylindrical sections, about 20½ inches in diameter, of tongued and grooved wood staves, bound with angle iron hoops. Each 3-ft. section is divided into quarters, two quarters being hinged together to make a half-cylinder. The halves are placed around the pile and fastened together with iron lock-wedges to make the completed cylinder.

The sequence of construction is as follows: The first 3-ft. section, which will ultimately be the lowest piece of the form, is fastened around the pile. The lower end of this section is provided with a special gasket which fits snugly against the pile, sealing the bottom end of the form. The section is filled with concrete consisting of one part cement, two of sand and three of pea gravel, and is then lowered by means of cables until there is room to place the second form section. This is bolted to the first, filled with concrete and the forms thus far filled are again lowered enough to allow placing the next section. This continues until the entire form and the pouring of concrete is completed, the bottom form having reached and penetrated the mud, the top being as high as desired. In this way the concrete is all placed above water and afterwards lowered to its final position. This feature avoids the difficulty of making the form entirely watertight and of pumping it dry before placing the concrete. The form is left in place about two days, and is then removed by pulling the iron lock-wedges, all of which are attached to a chain running up the side.

Under proper conditions, if the form is made reasonably tight and the concrete properly mixed, the lowering operation should be accomplished with little or no salt water getting into the mixture. If, however, the mixture is too dry or the coarse aggregate too large, it may drag on the pile surface while the form is being lowered and open up pockets in the concrete. Leaking sea water is likely to fill these holes and later become mixed in the concrete, giving poor results The process is likely to be more successful on piles in shallow water than on piles in deep water. The mixture

tends to separate somewhat, as it slides down the pile, and the greater the distance it has to slide the more is the likelihood of getting a poor mixture.

On November 6, 1920, in the presence of the Committee, Mr. Camp coated two experimental piles by his process. These were full-sized piles, but were experimental

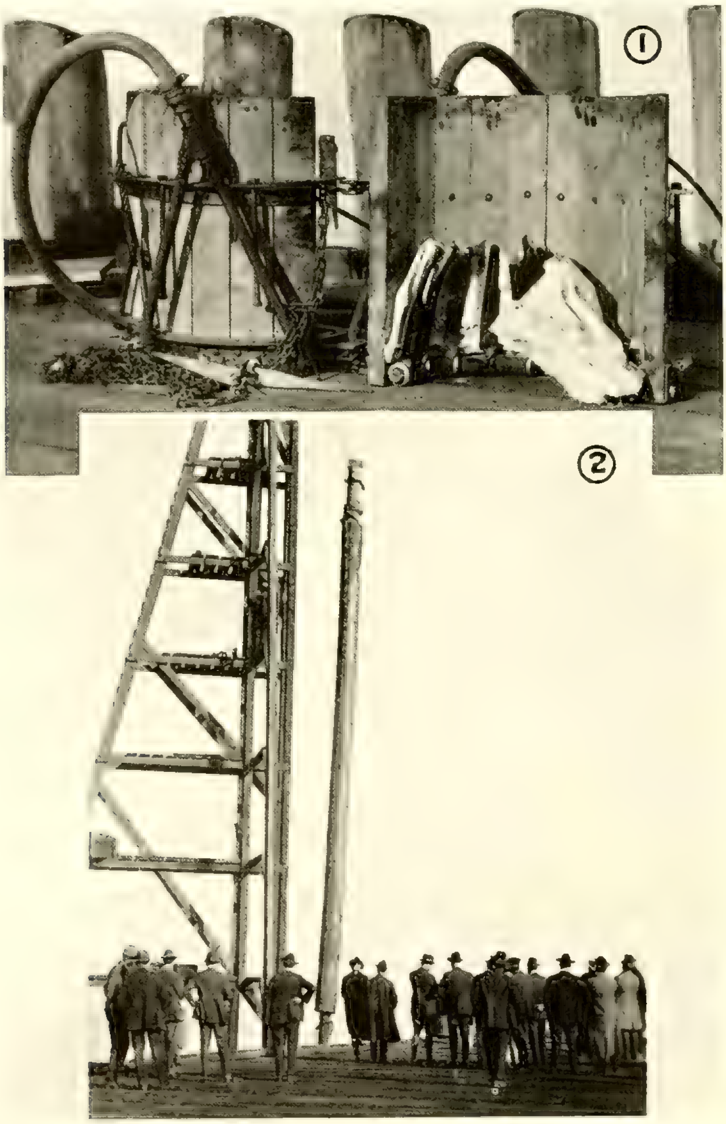

Fig. 46. (1) Lower forms used in Camp process. Note metal fingers supporting canvas web, to keep concrete from dropping through.
(2) Pile jacketed with cement by Camp process, being pulled for examination.

in that they were merely set in the mud instead of driven, so that they could easily be pulled for examination. One of them was set in water 28 feet deep at low tide and the other in 18 feet of water at low tide, both in strong tidal currents. On the long pile, approximately 40 feet of concrete was placed, extending into the mud to a depth of 2.8 feet. This was done in 32 minutes. On the other the concrete was approximately 28 feet long and required 21 minutes to place.

On November 27, 1920, in the presence of the Committee, the long pile was pulled for examination. The upper half of the concrete was good except for a large laitance hole about four feet from the top. The lower half of the concrete was not in good condition and in some spots could be kicked to pieces. In other spots there was a thin shell of good concrete on the outside, while on the inside the material was like mud. The whole lower 15 feet of the casing was broken off without difficulty with a sledge hammer. On Wednesday, December 1, 1920, the shorter pile was pulled and the concrete was found in excellent condition.

The results of this test cannot be considered conclusive, however, since not enough piles were coated to show what the average results would be.

A large number of piles, reported to be about 2600, were protected during 1920 by this method at the dock of the California Wharf and Warehouse Co. at Port Costa. The length of the protection required was up to 28 feet, averaging about 15 to 18 feet. The cost of this work was reported to be about 50 cents per lineal foot for materials and $1.50 per lineal foot to the contractor to cover labor and other costs and his profit. The company employs an inspector to examine each finished coating very carefully, using a hook on a pole below water line. Defects found above water can be easily repaired. When defects are located below water, larger forms are used and a new jacket is cast over the first one. Only meagre data respecting the performance of this installation have been available to the Committee.

The advantages of this process are: (1) the possibility of repairing damaged piles in place, with little or no disturbance to the structure or interruption of business; (2) the possibility of coating piles at any stage of the tide; (3) rapidity of the work, and (4) the relatively short portion of the pile requiring protection. The disadvantages of the process are: (1) the danger of getting defective concrete, especially at the greater depths; (2) the danger of getting the concrete thin on one side and thick on the other, which is especially likely to happen if the pile is leaning or crooked; (3) the disturbance of the mud caused by removing the bottom form, which may leave wood exposed below the concrete, leaving it a question whether the holes thus formed will tend to fill up with mud, or whether an eddy will form and keep them scoured out; (4) mud scour, which may take place to a greater depth than provided for by penetration of the shell, leaving wood exposed below the concrete; (5) the absence of adequate reinforcement. The work must be done by a thoroughly skilled and responsible crew to insure good results in any case.

Several thousand piles have been treated by this process in the San Francisco Bay region. Unfortunately, accurate data on the number of piles protected by this method in its largest installations, the percentage of good results and the average life obtained could not be secured. It is only fair to say, however, that since the earlier days of the Committee work the examples of this process which have been examined have indicated a considerably higher percentage of good results than did the experiments of 1920.

Newsome-Squire Process

This process, introduced in 1921, consists of a concrete protection for a timber pile, constructed by placing the form, and then pouring the concrete simultaneously with the driving of the pile. The impact of driving is thus utilized to secure thorough compacting of the concrete. Insufficient time has elapsed to judge the effectiveness of the process.

PRE-CAST TYPE

Pre-cast concrete pile protections have been of two general forms. In the first of these the reinforced concrete protective shell is cast, upon land, entirely separate

from the previously driven wooden pile over which it is afterwards slipped, in place. This process makes appropriate to this form the name, often applied to all pre-cast pile protections, pre-cast concrete jacket. In the other form of pre-cast protection the concrete or mortar covering is fabricated directly upon the undriven pile, over attached reinforcing, and the pile and concrete covering are driven as a unit. Since this covering is usually applied with a cement gun, the name gunite is generally applied to this form of pile. The higher average quality of fabrication made possible by pre-cast construction, as well as the assurance of quality through more effective inspection, are advantages of very real weight.

The Pre-Cast Pile Jacket

Most of this type of jackets have used single, full-length casings, although sectional jackets have been designed with special details for connecting the sections as they were lowered into position. The patent, in fact, taken out by F. A. Koetitz, by whose name the single-piece pre-cast pile jacket has come to be called locally, was for a special design of pre-cast sectional pile jacket, rather than the more widely used single-piece form. The pre-cast sectional concrete jacket has never attained any popularity in this region.

Pre-cast concrete pile jackets may be round, octagonal, square, or of any other desired external section; inside they are usually round and of enough greater diameter than that of the pile to allow for irregularities in the latter and for the insertion between pile and jacket of a pipe with which to pump out and grout the space. The minimum thickness of shell is usually 2½ to 3 inches. When the wooden pile is driven at the time that the concrete protection is to be applied, if the bottom is soft, there may be fastened to the pile, at a point which will be several feet below mud line, blocks upon which the concrete cylinder will rest.

Pre-cast jackets of this type were first used on the San Francisco waterfront in 1908, and between that time and 1911 approximately 300 were constructed, chiefly in bulkhead wharves.

In 1911, Pier 17 at San Francisco was built on 1130 of these piles. The cylinders used were 26 inches in diameter, outside dimensions, and the walls were 3 inches thick. They were driven about 8 feet into the mud and extend upward to the underside of the steel deck beams. The wooden piles were cut off at about mean sea level, and the cylinders above the heads of the piles were filled with concrete, into which the beams were anchored by steel bars. The space between the wood and concrete was filled with sand in the early part of the work, but later a grout filling was used.

The condition of these piles at the present time is excellent. A careful examination from a boat showed no defects above low water. In 1921, a diver made an examination from low water to the mud line of 50 piles selected at random and covering the entire length and width of the pier. No defects of any kind could be discovered. Of the several hundred of these piles driven in bulkhead wharves along the San Francisco waterfront between 1907 and 1922, some are now showing small defects but the majority are in good condition and all are still in service.

The success of these early installations has resulted, after a considerable period of quiescence, in a renewed adoption of this protection. It was used in the new Pier 50 whose construction was commenced in 1925 by the Board of State Harbor Commissioners in San Francisco. It was also used in the same year by the Alaska Packers Association in the Encinal Terminal wharves in Alameda and by the Harbor Commission of San Diego in the construction of a pier and a bulkhead wall for tideland reclamation.

The following description of these recent installations of pre-cast concrete pile jackets is quoted from Mr. Frank G. White, Chief Engineer of the California Board of State Harbor Commissioners (writing in 1925)*.

"Pier 50, the inner unit of which is now under construction, has a width of 386 feet and when completed it will have a length of 1450 feet. At present it is being built 600 feet long. There are two flush tracks on each side and three depressed tracks and a driveway down the center. The sections under the outside tracks, having a width of 30 feet on each side, are of creosoted pile and timber construction. The remainder of the structure is of reinforced concrete on jacketed piles. The conditions are ideal for this type of construction as the bottom is of such a nature that piles from 70 to 90 feet in length are required while the jackets are only from 26 to 41 feet in length. In previous work by this method the wooden piles were driven tip down as is the usual custom. In Pier 50, however, they are being driven butt down. This gives increased bearing value and permits of using jackets 14 and 16 inches in inside diameter instead of 18 to 20 inches as would be necessary if they were to be placed over the butts of large piles. It also facilitates the introduction of pipes for pumping and grouting. The jackets are circular on the inside and octagonal on the outside, the corners being chamfered on a 4-inch bevel. Two sizes of jackets were used depending on the length, the minimum outside dimensions being 20 and 22 inches and the minimum thickness of shell 3 inches. The reinforcement consists of 8½-inch square deformed bars spirally wrapped with No. 6 wire on 4-inch pitch. The longitudinal bars protrude 2 feet for bonding into the deck structure.

"The concrete consists of one part of cement to 4½ parts of graded aggregate. It is mixed fairly dry and is thoroughly tamped and spaded after being deposited in the forms. The jackets are kept

Fig. 47. Pre-cast concrete jackets in place over piles. Alaska Packers' Assn., Alameda. (*Moulin Photo.*)

covered with wet burlap for two weeks and are not handled for 30 days after being cast. As they are set in position over the piles, the mud is forced out by means of a gasket made of old rubber hose, after which they are sealed by grouting under water. When this grout has set the space between the jacket and pile is pumped out and filled with concrete. The deck is of reinforced concrete construction.

"The wharves at the Encinal Terminals are being constructed along one side of a dredged slip about 1500 feet in length. Except for modifications in design on account of different local conditions

*Paper, "Concrete Jacketed Piles," presented before the 1925 meeting of the Pacific Coast Association of Port Authorities.

the construction is similar to that at Pier 50. Municipal Pier No. 2 at San Diego is 1000 feet in length and 500 feet in width and consists of a suction dredge fill with reinforced concrete wharves over the slopes at the sides and outer end. Concrete jacketed wooden piles were used in the two inner rows and reinforced concrete piles in the remainder of the work.

"The fact that the jackets are capable of adjustment as to position over the piles was taken advantage of in the bulkhead walls which were built in conjunction with the piers and wharves referred to and also in the wall which is now under construction in San Diego. In this wall which is 3000 feet in length, the jackets are square on outside except for small chamfers on the corners. The piles are driven on 10-foot centers and as the jackets are set they are turned so that the faces make an angle of 45 degrees with the axis of the wall and so that they are vertical. Pre-cast reinforced concrete slabs are used to close the intervening spaces and each jacketed pile is anchored into the fill on the inshore side by means of a reinforced concrete tie and a timber anchor. This is typical of the work at the Encinal Terminals except that brace piles were used instead of inshore ties. In Municipal Pier No. 2 at San Diego the jackets were set square with the axis of the wall and the slabs rest against the flat face. The same detail is being used in Pier 50 in San Francisco.

"It will be clear from the descriptions given above that the pre-cast concrete jackets as at present used are in effect reinforced concrete piles with wooden cores. As the relative lengths of the jacket and pile approach each other due to bottom conditions a point is reached at which it is more economical to omit the wooden core and use a solid concrete pile. This was done at the outer end of Pier 50 and in the outer rows in Pier No. 2 at San Diego. The adaptability to varying conditions, the rigidity and durability of the resulting structures and the relative economy are the principal characteristics of this type of construction."

When the casings are made and placed with sufficient care, including adequate bottom penetration of the concrete shell to insure that the wooden pile will not be exposed by subsequent dredging or scour, good protection can be obtained. Their durability is then affected by the factors which ordinarily influence the life of good concrete in sea water. There is some danger of developing cracks during handling,

Fig. 48. Concrete jacketed pile, pre-cast type, showing typical rusting crack above high tide level. From bulkhead between Piers 28 and 30, San Francisco; driven 1909.

which would admit sea water to the reinforcement and permit rust to form, but this can be prevented by proper care in the handling. The cost is relatively high and a long life is therefore necessary to justify it.

GUNITE PILE PROTECTION

This is a pre-cast reinforced concrete cylinder or sleeve, applied to the wooden pile over previously attached reinforcement, in the initial fabrication; or fabricated separately and applied subsequently to the pile, in place. This is done by shooting cement grout on to the reinforcement fabric with a cement gun. This process has been used in the San Francisco Bay region since 1912, when a number of gunite coated piles were driven in a marine railway in the bay. Since then it has been used here chiefly by the Shell Company of California. The service life is not yet complete, but they seem to have given excellent satisfaction thus far. The cost of the protection is relatively high. An installation of 1450 of these piles was also made in 1922 at the Port of Tacoma, Washington.

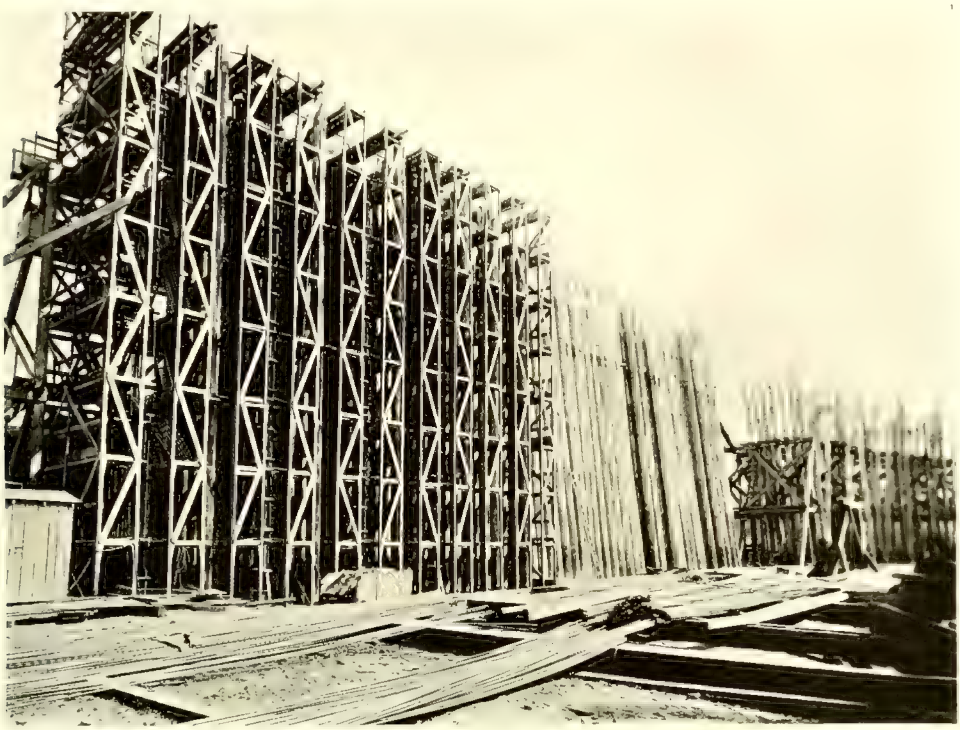

Fig. 49. Gunite concrete piling and plant, Los Angeles.

REINFORCED CONCRETE SUPPORTS

Reinforced Concrete Piles

Reinforced concrete piles have been used both on the Oakland and San Francisco waterfronts since 1911. Along the latter, more than 11,000 have been used in the construction of five piers as well as numerous wharves, ferry slips and building foundations. The first, used in 1911, were for supports for aprons of passenger ferry slips. In 1912 a section of bulkhead wharf adjacent to Pier 17 was constructed with them. Pier 35 constructed in 1914-15 was the first to be built exclusively with reinforced concrete piles.

Of the numerous installations made during the last several years no serious defects have been noted in the portion of the piling below high water level. In the older structures, however, cracks due to the rusting of embedded steel have appeared be-

tween high water level and the wharf deck. In this portion of the pile they are easily observed and repaired, as contrasted to deterioration below low water which cannot easily be observed.

As a result of experiments and observations, the engineers of the Harbor Board are confident that in all future construction, deterioration due to rusting of embedded steel can be retarded, if not entirely prevented, by certain simple expedients, such as embedding the steel deeper in the concrete in the section above low water, having about three inches of concrete covering between the steel and the pile surface; using galvanized steel; periodically coating the concrete surface with asphalt, paraffine or other waterproofing.

Square piles have been used exclusively in San Francisco work, the size varying from 16 inches square for lengths up to 45 feet to 20 inches for lengths up to 105 feet. The points are tapered down on two sides for a distance of from 6 to 10 feet to a width of 10 inches. The reinforcement consists of square corrugated bars with spiral wrapping of No. 3 wire. The amount of steel varies according to the pile length from four ¾-inch to six 1-inch bars.

In making concrete piles, the established practice is to use a mixture of one part cement to five parts aggregate. The different sizes of aggregate, usually four, are brought on the ground separately and proportioned so as to obtain as dense a mixture as possible. Thorough mixing and tamping are required and the mortar is spaded against the forms. All piles are cured at least 45 days before driving. Piles up to 90 feet in length are lifted by a 4-point suspension—the cables being attached at the

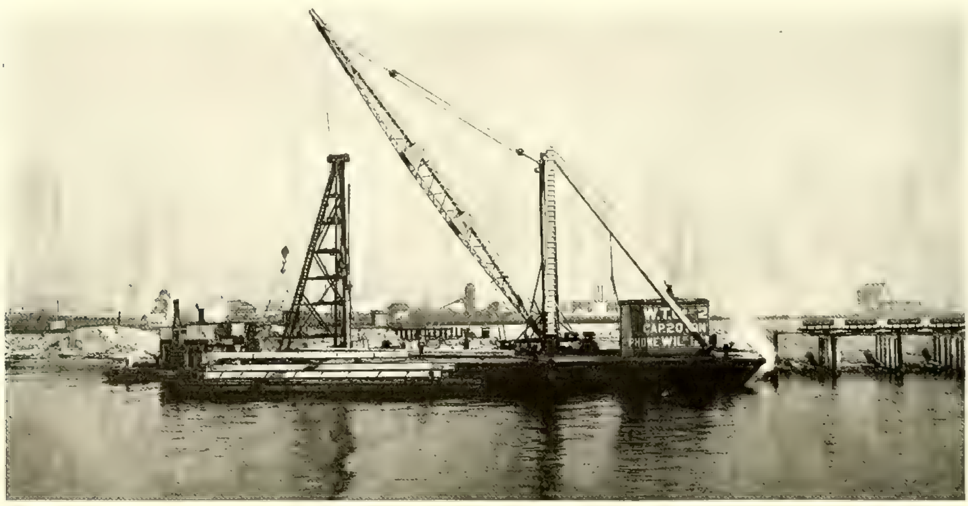

Fig. 50. Handling and driving pre-cast concrete piles, Berth 230, Los Angeles harbor.

center of each quarter of the pile; those over 90 feet long are lifted by a 5-point suspension, or at the center of each fifth of the pile. Driving is done with a heavy steam hammer, assisted by water jetting where necessary.

Some of the advantages possessed by this type of construction are the rigid, substantial substructure which results and the possibility of the use of a permanent, fire-proof superstructure. The certainty of securing more careful inspection and workmanship of pre-cast piles built on land makes them more satisfactory than cast-in-place concrete cylinders. The objections to this type of construction are the high first cost and the length of time required for construction of the pile; the high cost of

placing and driving the pile and danger of damaging it in that process; and the uncertainty as to length of life which can be secured.

With reference to both reinforced concrete cylinder and reinforced concrete pile construction, many engineers are of the opinion that the increased cost of this construction is not justified by the degree of permanence so far exhibited. The principal factor which has influenced the early development of this construction in this locality has been the demand for fire-proofing in waterfront structures where cargoes are concentrated aggregating in value many times the cost of the structures. As frequently happens, the pioneer has paid heavily for the experience of blazing the way. All the early structures were built before the modern scientific studies of concrete construction were disseminated, at a time when not only was the danger of excessive water and sand contents unknown but such excesses were even thought beneficial, and when concrete of any thickness was considered as efficient protection from the corrosion of steel.

Notwithstanding defects which will admittedly lessen the durability of the actual structures built, engineers who are familiar with these structures believe that they indicate the essential soundness and value of the type when constructed with safe-

Fig. 51. Handling 105-foot concrete pile with 5-point suspension, Pier 3, San Francisco. (*Board of State Harbor Com's. Photo.*)

guards whose value is now universally recognized. In general it may be stated that high class reinforced concrete cylinder and reinforced concrete pile construction on San Francisco Bay gives promise of outlasting all other types of substructure support with the exception of mass concrete construction. Its high cost necessarily limits its use to structures in which long economic life, fire risk or difficulty of replacement justifies increased expense. On the other hand it may be observed, however, that since

their construction the value of the San Francisco piers has been substantially enhanced by the progressive rise in construction costs, a tendency which is seldom taken into account by advocates of more temporary construction.

REINFORCED CONCRETE CYLINDER COLUMNS

This type includes various forms of reinforced concrete column supports, bearing either directly on hard substrata or on pile foundations. It has been used in the construction of fourteen piers on the San Francisco waterfront. While the details of design vary somewhat in the different structures, the cylinders used in Pier 28, constructed in 1912 and 1913, are typical of this type of construction.

Pier 28 is 150 feet in width and 677 feet in length. It is supported on 452 reinforced concrete cylinders which are spaced approximately 15 feet apart in both directions. The cylinders are $3\frac{1}{2}$ to 4 feet in diameter and are supported on bases from 5 feet to 7 feet in diameter, which rest on a compact bed of sand, clay and gravel at a depth of from 40 to 70 feet below low water.

The cylinders and bases were constructed in cylindrical open steel caissons about 8 feet in diameter which were sunk to the required depth by dredging out inside with orange-peel buckets and driving with a pile driver as the excavated material was removed. After the caissons were sealed by driving into the hard bottom the water was pumped out and the bottom was excavated by hand to an even bearing. The cylinder forms were built up with 2-inch stave lumber hooped with steel bands, and the reinforcement consisted of $\frac{7}{8}$-in. square bars spirally hooped with No. 0 wire.

The concrete in the cylinders was mixed in the proportion of one part of cement to six parts of aggregate. The aggregate consisted of several sizes of sand and crushed rock so as to give a graded mixture. The concrete was poured through a jointed pipe and was tamped and spaded so as to fill the 3-inch spaces between the reinforcing steel and the forms. After the concrete had set not less than 24 hours the caissons were pulled, the wood stave forms being left permanently in place.

The cylinder type of construction has proved satisfactorily where the work was properly done. The structure is fire-proof and permits of the construction of a fire-proof shed which is not feasible in this locality on a timber substructure. It is rigid and permanent in character and the maintenance is reduced to a minimum. The most serious disadvantage is the difficulty of securing thoroughly satisfactory work, particularly on the outside surface of the cylinders and at the joints. Unless the mortar is well spaded to the outside so as to afford the necessary protection for the reinforcing steel there is pitting of the surface, particularly between tide levels. In pouring the cylinders the work is carried up to the underside of the deck structure in one operation and completed after the placing of the deck forms. In pouring these long cylinders laitance is apt to collect at the top and unless this is removed down to solid concrete before the next section is poured, a plane of weakness results. A considerable number of cylinders have been repaired due to these defects but the fact that large numbers constructed from 9 to 16 years ago are in first class condition proves that satisfactory construction of this type is entirely feasible.

Reinforced Concrete Caissons

The Harbor Board has developed a method of constructing concrete piers in which pre-cast reinforced concrete caissons are placed and filled solid with concrete. The caissons thus serve as watertight forms for the concrete, and afterwards become the permanent outer shells of the piers.

Fig. 52. China Basin Terminal San Francisco. Concrete caisson construction, showing tops of caissons in place, piles being driven inside caissons and concrete being poured.
(*Board of State Harbor Com's. Photo.*)

This type of support was used in constructing the China Basin Terminal. (See p. 30.) The caissons had a rectangular section 7.5 ft. by 20 ft. and were 47 to 50 ft. high; the rectangular section was divided by partitions into three compartments. The outer wall or shell was about 7 inches thick, the partitions 6 inches thick.

Fig. 53. Construction of California-Hawaiian Sugar Refining Co. warehouse at Crockett, showing ops of reinforced concrete piers and forms in place for groined arches.

After the caissons were constructed on shore, the ends were sealed with timber bulkheads, and they were launched and floated to the site. They were then sunk into position, their lower ends resting in holes previously excavated in the mud down to hardpan. The bottoms of these holes were covered with a layer of crushed rock. Five piles were then driven in each of the three compartments, the cut-offs being several feet above the bottom of the caissons. The bottoms were sealed by placing about 12 feet of tremie concrete. The caissons were then pumped dry and filled solid with concrete.

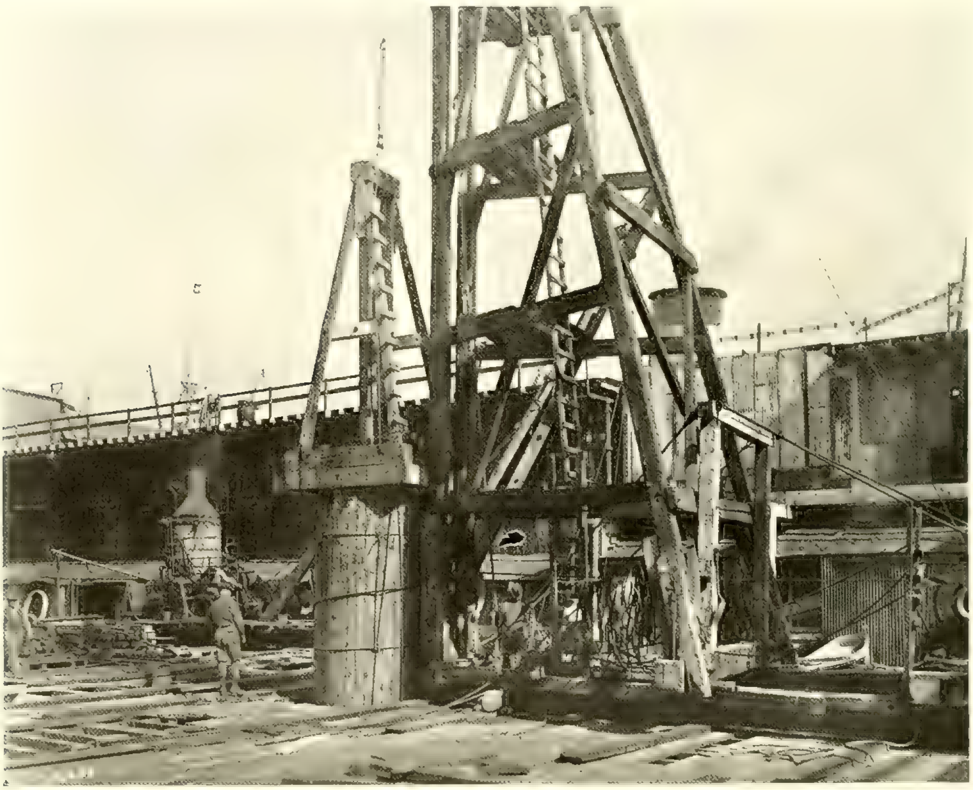

Fig. 54. Driving cylindrical forms, California-Hawaiian Sugar Refining Co. warehouse, Crockett. Note outer hoops and rods for pulling wedge pins.

LARGE MASS-CONCRETE CYLINDER PIERS CONSTRUCTED IN OPEN REMOVABLE TIMBER CAISSONS

The California-Hawaiian Sugar Refining Co. has developed a large mass-concrete substructure pier, required because of the extremely heavy floor loadings of their warehouses, at their Crockett refinery. The floor load in question is about 2,000 pounds per square foot. The concrete piers are 6 feet in diameter and are carried down to hardpan, in some cases 60 feet below the wharf level. No reinforcement is used. They are spaced at about 16 feet centers in both directions and support a floor system of groined arches with a 9-inch floor slab.

The sequence of construction is as follows: Cylinder forms, with an inside diameter of 6 feet and lengths up to 50 feet, are made with 4, 6 or 8-inch redwood staves. The individual stave pieces are held in position in the form by removable interior

angle iron hoops and by removable exterior hoops of round bars, spaced several feet apart. The interior hoops are bolted, while the exterior hoops are locked with wedge-pins all connected to a chain running up the side of the form. When the form is completed it is lifted and driven into position with a modified pile driver, the "hammer" being built of large timbers, having a driving face several feet square. When the form has been driven to refusal the water is pumped out and the mud removed with a small orange-peel bucket. The bottom excavation is then continued by hand down to hardpan. The interior hoops are then removed and the concrete poured. After allowing sufficient time for the concrete to set, the outer hoops are removed by pulling the wedge-pins. The stave pieces can then be loosened and pulled and re-assembled for further use. These serve for several piers before being discarded.

SPECIFICATIONS FOR CONCRETE IN MARINE STRUCTURES, WITH OUTLINE OF PRACTICE

The treatment of this subject has been undertaken by the Committee, not in competition with existing able discussions of the general subject of concrete, but from a conviction that this specific phase, appropriate to the attention of this Committee, has not been adequately considered in previous discussions. The material presented has been prepared by a special sub-committee consisting of H. J. Brunnier, Consulting Structural Engineer, San Francisco, and H. E. Squire, Assistant Engineer, Board of State Harbor Commissioners, San Francisco.

This Outline of Practice with Specifications is intended to cover only the phases of design and construction which affect the durability of concrete exposed to sea water and to present practical working specifications for this class of work. Its application is further limited to Pacific Coast conditions, which are free from extreme temperatures and ice action.

The general requirements for materials and workmanship are presented in the form of a working specification. This is followed by a brief discussion of the application of the specifications in the design and construction of different types of structures under varying conditions of exposure. The specifications must be read in the light of the specific application to which they are limited, as thus discussed.

COMMITTEE SPECIFICATIONS FOR CONCRETE IN MARINE CONSTRUCTION

Prepared by H. E. Squire

Approved by the Committee, 1922

SECTION A

Materials

1. Materials for the work shall consist of requisite amounts of Portland cement (all of which will be furnished to the Contractor by the Owner), fine aggregate, coarse aggregate, mixing water, reinforcing steel and asphaltic coating.

2. *Testing and Inspection.* All materials shall be delivered on the work, or submitted as samples when so directed, in ample time to permit inspection in order that they may be tested and the proper directions given for their use.

3. *Cement.* Portland Cement shall conform to the "Standard Specifications for Portland Cement" (Serial Designation C 9-21) of the American Society for Testing Materials unless otherwise authorized. Cement will be furnished to the Contractor by the Owner. The Contractor shall haul, unload and store the cement in a tight shed to be constructed by him on or near the work, and shall be responsible for the proper care of the cement and for the return of all empty sacks in as good condition as when delivered to him. The Contractor shall pay for all cement which is damaged or stolen after being delivered to him and for all empty sacks rejected for damage.

4. *Fine Aggregate.* The fine aggregate shall be clean river or beach sand containing not more than three (3) per cent of loam, mica or organic matter. It shall range in size from fine to coarse within the following limits:

Passing No. 4 sieve—not less than 95 per cent.

Passing No. 50 sieve—not more than 30 per cent.

If necessary, grading shall be obtained by mixing fine and coarse sand.

5. *Coarse Aggregate.* The coarse aggregate shall consist of crushed rock or gravel or combinations thereof, having clean, hard, strong, uncoated particles free from injurious amounts of soft, friable, elongated or laminated pieces, shale, organic or other deleterious matter.

Coarse aggregate shall range in size from fine to coarse within the following limits:

Passing 1½-inch sieve—100 per cent.
Passing ¾-inch sieve—from 40 per cent to 75 per cent.
Passing No. 4 sieve—not more than 10 per cent.
Passing No. 10 sieve—not more than 2 per cent.

If necessary, grading shall be obtained by mixing two or more screened aggregates.

6. *Water.* Water for concrete shall be clean, fresh and free from deleterious substance.

7. *Reinforcing Metal.* Metal reinforcement shall be of a quality and character meeting the requirements of the "Standard Specifications for Billet Steel Concrete Reinforcing Bars" (Serial Designation A 15-14) of the American Society for Testing Materials, "Structural steel grade," except that the provisions for machining deformed bars before testing shall be eliminated.

All bars called for on the drawings are square and of the following net sections:

⅜″ bars, net section	0.14 square inch
½″ bars, net section	0.25 square inch
⅝″ bars, net section	0.39 square inch
¾″ bars, net section	0.56 square inch
⅞″ bars, net section	0.77 square inch
1″ bars, net section	1.00 square inch
1 ¼″ bars, net section	1.56 square inch

All bars shall have a satisfactory mechanical bond approved by the Engineer. Round mechanical bond bars may be substituted, provided they have the above net sections. Twisted steel bars will not be accepted as having a satisfactory bond. Where reinforcing steel is called for galvanized, it shall be uniformly covered with a spelter coating of two and one-half ounces of spelter per square foot of surface area.

The contractor shall provide detail drawings showing his schedule for bending and splicing reinforcement. Three copies shall be submitted to the Engineer, one of which will be returned to the Contractor after being approved.

8. *Asphaltic Coating.* The asphalt used for the paint coat shall be homogeneous and free from water. The loss on heating, according to the method of the American Society of Testing Materials (Serial Designation D 6-20), shall be not more than 3 per cent. After such heating the penetration of the residue shall be not less than 50 per cent of the original sample. The penetration of the original sample shall fall between 90 and 110, using A. S. T. M methods for penetration (Serial Designation D 5-21). The softening point shall be between 100 and 90° F. using the hook and cube method. (A. S. T. M., D 61-20.)

SECTION B

Proportions

1. *Unit of Measurement.* The unit of measure shall be the cubic foot. One sack of Portland cement weighing ninety-four (94) pounds shall be considered as one cubic foot.

2. *Method of Measuring.* Each of the constituent materials shall be measured separately by volume. The devices for measuring shall be sufficiently accurate to insure a uniform mix and shall be subject to approval of the Engineer. The water tank shall be so arranged that the water can be measured and regulated definitely and the device used shall be subject to approval by the Engineer.

3. *Proportions.* The classification of concrete used in different parts of the structure will be designated by the proportions of cement to the total fine and coarse aggregate. The quantity of water and the proportion of fine to coarse aggregate will be determined by the Engineer from tests on the grading of aggregate and the requirements of the construction. In general the quantity of water will be as small as the tamping hereinafter specified will work into a homogeneous plastic mass. The quantity of fine aggregate will be as small as will adequately fill the voids of the coarse aggregate and will not exceed one-third of the total aggregate. The Contractor shall measure and proportion the cement, water and aggregate in accordance with the general classification designated in the plans and the detailed proportions determined by the Engineer.

SECTION C

Manipulation

1. *Mixing.* All concrete shall be mixed by machine of a type approved by the Engineer. The arrangement of hoppers, water tank and measuring devices shall be such that proportioning can be readily controlled by the Engineer or his representative.

The mixing shall be continued for a minimum time of one minute after all ingredients are assembled in the mixer before any concrete is drawn off, during which time the mixer shall rotate at a peripheral speed of 200 feet per minute. The consistency of the mix will be controlled by the Engineer in proportioning the water. In general, the consistency shall be as dry as can be used with the tamping hereinafter specified. Excessively wet concrete shall be wasted and the cement contained charged to the Contractor. Any excess of concrete which has been standing long enough to take an initial set shall not be retempered and used in the work.

2. *Transporting.* Unless otherwise authorized by the Engineer, concrete shall be transported from mixer to forms in approved containers such as buckets, buggies, or barrows. Spouts, troughs or devices which may affect the consistency or limit dry consistencies shall not be used unless expressly permitted by the Engineer. In case separation or other deleterious changes occur during transportation, the concrete shall be dumped into a hopper and remixed by shovelling before being deposited in the forms.

3. *Tamping.* After depositing in the forms, the concrete shall be thoroughly worked with tools of an approved type. For the purpose of insuring thorough compacting, the contractor shall furnish in addition to wheelers, dumpers and finishers, one tamper for every two yards of concrete and fraction thereof placed per hour, who shall do nothing other than spread and work the concrete as directed by the Engineer. When the area of deposit is sufficient, concrete shall be spread in six-inch layers and each layer thoroughly rammed to a plastic mass before the succeeding layer is placed. When the area between forms does not permit of spreading, the concrete shall be compacted both by rodding from the surface and by vibrating the forms with mallets and hammers.

4. *Joints.* All joints shall be made at locations designated by the Engineer. When work is begun on any section it shall be carried on continuously to the line or joint previously determined. Unless otherwise directed, joints shall be framed with offsets, keys or reinforcing dowels approved by the Engineer. When concrete is deposited against a hardened layer or joint, the entire surface shall be cleaned, roughened with a pick, made thoroughly wet, and slushed with neat cement paste.

5. *Forms.* Forms shall be constructed of steel or of surfaced lumber of sufficient strength to hold the concrete in position, and tight enough to prevent any leakage or washing out of mortar. They shall be correct in shape and dimension and shall be properly braced or tied together so as to maintain shape and position. Unless otherwise specified all right-angled corners shall be chamfered by means of mouldings or beveled strips.

Before any concrete is deposited, all dirt and foreign substances shall be removed and the forms thoroughly hosed out and wet down.

Forms shall remain in place until in the judgment of the Engineer the concrete has hardened sufficiently to sustain its own weight and to resist loads or impacts which are likely to occur during construction.

6. *Curing.* The surfaces of newly placed concrete shall be carefully protected from rapid drying by covering them with sand or burlap which shall be kept wet for a period of two weeks after depositing concrete. No formed surfaces shall be exposed either in air or under sea water until 48 hours after depositing concrete.

Pre-cast members shall not be handled until 28 days after depositing concrete. Pre-cast piles or other members subject to impact shall not be driven until 40 days

after depositing. Any pre-cast members cracked during handling shall be inspected by the Engineer and if rejected by him shall be removed from the work.

7. *Finishing.* Surfaces shall be inspected by the Engineer when forms are stripped and should any voids, stone pockets or poor joints be discovered, they shall be cut out in such a manner as to form a key and then filled with cement mortar composed of one part Portland cement to one and one-half parts fine aggregate.

All surfaces above mean tide level which are exposed to sea water spray shall be given a priming coat of asphalt cut with distillate and a final coat of hot asphalt of the quality hereinbefore specified.

8. *Concreting Under Water.* Concrete shall not be deposited in sea water or under the sea water unless authorized by the Engineer. When placed in sea water, concrete shall be discharged through a water tight tremie into prepared pockets of such capacity that each can be completed without interruption of the flow of concrete. The tremie pipe shall be of sufficient size to permit the free flow of the plastic concrete, and the arrangement shall be such that the tremie can be readily raised or lowered without interruption of the flow from a hopper or mixer until the pocket is completed. The size of pipe, dimensions of pockets and capacity of hopper and mixer shall be determined by the Engineer and will depend upon the depth of water and the size and dimensions of the pockets to be filled. In operating, the top of the tremie pipe shall be plugged with hay or straw to be forced ahead of the charge of concrete. After the charge is started, the flow of concrete into the tremie shall be carried on continuously without interruption until the pocket is completed. The lower end of the tremie pipe shall be kept embedded in the concrete to such a depth that water cannot be forced back into the pipe through the plastic concrete.

Tremie concrete shall be proportioned at least one part cement to four parts aggregate. The consistency of the concrete shall be mushy so that it will flow readily without separation.

SECTION D

Embedded Reinforcing Steel, Structural Steel and Timber

1. *General.* If steel or wood is embedded at more than six inches from the surface, the structure shall be considered of "simple" type and shall not require special treatment in the concrete coating. If embedded at less than six inches, the concrete coating shall be considered primarily as a protection requiring special treatment. Concrete in protected composite structures shall be proportioned one part cement to five parts aggregate.

2. *Steel Reinforcement.* Unless otherwise specified reinforcing bars shall be placed at least three times the bar dimension from any exposed surface and at least five times the bar dimension from adjacent parallel bars. If specified to be placed at less than the above minimum depth and spacing, metal reinforcement in that portion of the structure above high tide and directly exposed to sea water spray and air shall be galvanized. Spacing from exterior surfaces shall be maintained by wiring to pre-cast mortar blocks approved by the Engineer; interior spacing by wires or steel chairs approved by the Engineer.

Reinforcing bars shall be bent to the shape and placed in the exact location and with the spaces shown on the drawings or called for in the specifications. Steel shall be cleaned of all mill scale or rust scale before being positioned. All bars unless otherwise noted or shown on the plans shall be continuous. Splices may be introduced only when authorized by the Engineer, who will determine the location and length of lap.

Reinforcing steel shall be in place in the forms a sufficient length of time before depositing concrete to permit inspection and approval by the Engineer.

3. *Structural Steel.* Embedded structural steel shall be coated with at least $2\frac{1}{2}$ inches of concrete. The protective coating shall be reinforced with galvanized wire mesh of at least No. 13 wire on 4-inch centers embedded 1 inch from the surface. Before structural steel is coated with concrete it shall be given two coats of red lead, one shop coat and one field coat, and a final coat of graphite paint.

4. *Timber.* Embedded timber, such as encased piles, shall be coated with at least $2\frac{1}{2}$ inches of concrete placed in the dry and thoroughly tamped. The protective coating shall be reinforced with galvanized wire mesh of at least No. 13 wire on 4-inch centers embedded 1 inch from the surface. Concrete protections of embedded timber members shall extend from above high tide to at least 3 feet below the mud line.

SECTION E

Constructing and Driving Concrete Piles

1. *Reinforced Concrete Piles* shall be composed of one-to-five concrete of the quality hereinbefore specified and shall be constructed to the dimensions and of the shape shown on the plans. Reinforcing steel of the size and quantity shown on the plans shall be placed in the manner hereinbefore specified. Each pile as it is cast shall be dated and no piles shall be handled until at least forty (40) days after being cast. In handling, piles shall be uniformly supported with slings or skids to prevent cracking or other damage. The method of handling shall be satisfactory to the Engineer and any pile cracked or damaged in handling or driving which is rejected by the Engineer shall be removed by the Contractor and replaced without extra cost to the Owner.

Piles shall be accurately spaced and driven to the depths shown on the plans, or to refusal, as the Engineer may direct. Unless otherwise authorized the driving shall be done with a steam hammer having a striking part weighing 5,000 lbs. and a normal stroke of 36 inches. If required by the Engineer, a water jet shall be used simultaneously with the driving. Where piles are driven into loose rock or rip rap, a steel point bull-dozer shall be driven at the location of each pile immediately preceding the driving of the pile. Pile heads shall be stripped of concrete to a neatly cut square face at the cut-off line shown on the plans. In case cracking due either to stripping or to driving extends below the cut-off line indicated, the stripping shall be extended until a square face of uncracked concrete is obtained. If by order of the Engineer piles are not driven to the elevations shown on the plans, the Contractor shall cut them off and strip the tops without additional cost.

2. *Concrete Jacketed Piles* shall be made up of a timber pile encased in a concrete coating from below the mud line to above the high tide line. Unless otherwise specified concrete coatings shall be precast as hollow casings which are placed in position and grouted after the pile has been driven. Pre-cast concrete coatings shall be constructed of the materials and in the manner specified above for reinforced concrete piles. The depth of penetration below the mud line shall be determined by the Engineer. The space between pile and casing shall be sealed at the bottom and pumped out before filling with grout.

APPLICATION OF SPECIFICATIONS TO CONSTRUCTION CONDITIONS

The problem of durability in marine concrete construction has become confused through the general grouping of all sea water exposed structures without regard to many factors which affect durability, irrespective of the quality of concrete. The influences affecting durability may be combined for study and discussion as those relating to the type of structure exposed and those relating to the nature and intensity of exposure. Effects of type include such considerations as size and mass of structure;

the rigidity or flexibility of its members; the interior structure of members; the depth of concrete encasements over steel or wood and the general form or shape of structures and members. Effects of exposure include such considerations as location with respect to wind and waves; the elevation with reference to tide; the nature of foundation substrata and the height above bottom; the nature and intensity of loadings, whether impact or static loads; the fluctuation of temperatures, both of air and sea water; the humidity of the air; and the frequency of wetting and drying out of the members.

While neither space nor data are available for a discussion of all these phases of type and exposure, structures may broadly be classified as "simple" or "composite" in regard to type, and exposure may be roughly judged as "Harbor" or "Ocean" exposure in regard to the intensity of disintegrating conditions. This classification covers in a broad way the essential differences in type considered in relation to durability, and visualizes the actual extremes of exposure to which structures are commonly subjected.

In this discussion, "Simple" structures will be understood as including homogeneous concrete structures greater than 12 inches in minimum section and having no steel, wood or other structural material embedded at less than 6 inches from the surface.

"Composite" concrete structures will be understood as including structures having members of reinforcing steel, structural steel or wood, embedded at less than six inches from the exposed surfaces. Complex members of concrete having sections less than 12 inches in dimension will for purposes of design and construction be classified with "composite" structures.

"Harbor" exposure will be understood as referring to structures located in protected harbors where the members are only occasionally exposed to sea water spray and are well braced and anchored against impacts.

"Ocean" exposure will be understood as referring to structures located in the ocean and exposed to continual spray from surf and heavy impact of waves.

Materials

Irrespective of type or exposure, the materials used for marine concrete construction should be high grade commercial products. The aggregate should of itself be dense, impervious sand, gravel or stone, not subject to disintegration in sea water.

Special attention should be given to the grading of aggregates and to the proportion of fine to coarse aggregate, with a view to securing the most impervious mortar consistent with the quantity of cement specified. This is accomplished by cutting down the quantity of mortar through using a properly graded coarse aggregate, thereby increasing the proportion of cement to fine aggregate, and by further increasing the quality of the mortar by using a properly graded fine aggregate. The uniformity with which aggregates hold their grading is also important. Materials having variable gradings which require frequent changes in proportioning should not be used. Coarse aggregate from ¼-inch to 1½ inch has been specified as the common and most desirable grading. Aggregate of larger size than 1½ inch requires so much care to prevent separation that its use is not recommended. For special conditions where sections of concrete are very narrow, coarse aggregate may advantageously be reduced to ¾-inch maximum size in order to facilitate depositing.

While it has been the practice in some cases to make special requirements as to magnesia and alumina contents of the cement and to increase the fineness of grinding beyond the requirements of the standard specifications, no cases of deterioration specifically attributable to cement of the quality specified have been reported. The mixing with the cement of chemical waterproofing compounds is not advised in marine

work because of the uncertainty of the reactions of these compounds with sea water. Sufficiently impervious mixes of concrete can be obtained by using the proper quantities of cement as discussed below. To insure the use of the full quantity specified, however, it is good practice to require the cement to be furnished by the Owner.

The use of sea water for mixing is detrimental to structures containing steel, because of accelerated rusting action. While sea water does not appreciably reduce the strength of the concrete itself, it produces an excessive amount of laitance and increases the likelihood of non-uniform, inferior work in all classes of structures.

Proportions

Proportioning of fine and coarse aggregate to produce workable mixes of high imperviousness requires skill and experience. In order to insure certainty of results, it is safer to provide properly graded screened aggregates as specified and combine them than to economize by using natural aggregates of unsuitable size and grading. Proportions should be determined with a view to keeping the quantity of fine aggregate as low as is consistent with the production of a workable mix.

"Simple" concrete structures having a "harbor" exposure may be considered permanent, for commercial purposes, if properly constructed with concrete proportioned one part Portland cement to seven and one-half parts aggregate.

Similar structures having an "ocean" exposure should be constructed of concrete proportioned one part Portland cement to six parts aggregate. If such structures are of sufficient section, they may be constructed of one-to-seven-and-one-half concrete with a facing of from 6 inches to 12 inches of one-to-five concrete. This veneer should be placed at the same time as the interior concrete.

Tremie concrete should be proportioned one part cement to four parts aggregate. It may be used for interior fill inside of impervious exterior walls. It should not be used for facing walls exposed to sea water, because of uncertainty with regard to quality.

"Composite" concrete structures having a "harbor" exposure should be composed of concrete proportioned one part cement to five parts aggregate. If the exposed surface of these structures above high tide is protected with periodic painting, they constitute a high-class fire-proof construction which is well suited for commercial purposes. Similar structures under the more severe conditions of "ocean" exposure should be proportioned one part cement to four parts aggregate.

As cracks and checks from impacts and tension account in a large measure for the disintegration of "composite" structures, it is not advisable to increase the cement above the proportions specified; additional protection being better obtained from a waterproof and air tight surface coating of such a composition that it will stretch or heal over small cracks.

Manipulation

Faulty manipulation in conjunction with excessive proportions of fine aggregate and mixing water account for almost all instances of disintegration of concrete in sea water. Durability is largely dependent on the imperviousness of concrete, which prevents sea water from freely entering the mass and breaking down the interior structure of the set cement. Mixes which are loaded with excessive quantities of fine aggregate and water to make them flow readily and save labor in manipulation produce absorbent concrete unsuitable for use in marine structures. On the other hand, excessively dry mixes or mixes with too little fine aggregate cannot be worked into a plastic mass under commercial conditions of concreting and are equally undesirable.

The problem is largely one of balancing the cost of cement and materials against the labor cost of manipulation, the richer mixes requiring less tamping and compacting than the poorer mixes. But no increase in cement will adequately offset excessively wet consistencies and careless manipulation, because of the separation of ingredients and formation of laitance which occur under such circumstances. Experience has proved that concretes of the proportions designated in these specifications and of such consistency that an average tamper can work two yards per hour into a uniform plastic mass are satisfactory for sea water use.

Methods of delivery which deposit concrete more rapidly than it can be tamped, or which are liable to require wet consistencies, are not suitable for use in marine concrete construction. For this reason small containers, the dumping of which can be controlled at the point of deposit, are preferable to chutes.

With regard to tamping, it is advisable to require an excess rather than a deficiency, in order to insure uniformity. Enclosed shapes having restricted openings should receive more than the specified amount of working. Mechanical tamping by means of pneumatic hammers, or by utilizing the impact of pile hammers, is sometimes advisable under special conditions. When such a mechanical means is used, however, the forms should be watertight; otherwise, owing to intense vibration, there is a tendency to draw the mortar away from the coarse aggregate.

Joints with set concrete are frequently sources of disintegration. This results, not only from failure to clean laitance and dirt from the old surface, but also because concrete deposited against rigid surfaces requires additional tamping and spading to make it plastic and requires more attention than when deposited against unset concrete, which vibrates and puddles with the new deposit.

Proper curing is probably of more importance for air exposed than for sea water exposed structures. Concrete immersed in sea water cures and sets under ideal conditions. While it is preferable to leave forms in place in order to protect the surface from impacts, no detrimental effects resulting from early exposure to sea water have been observed at San Francisco, either in construction work or in laboratory tests. For facilitating special construction, exposure in 48 hours may be permitted. Precast concrete is often reduced in strength and checked with surface cracks by exposure to the sun and wind, and should be protected against too rapid drying.

"Simple" concrete structures, whether subjected to protected "harbor" exposure or to "ocean" exposure, may be relied upon to resist sea water permanently if the concrete is intelligently mixed and deposited in accordance with the provisions of these specifications. The principal abuses to guard against are flooding the mix with excess water and failure to tamp and compact the mass thoroughly in the forms.

Another condition which makes for defective concrete in this class of structure is the flooding of the forms with sea water during concreting. When freshly mixed concrete comes in contact with sea water, magnesium salts are precipitated in considerable quantities, increasing the deposit of laitance. This, combined with separation and the laitance ordinarily caused by excess water, produces concrete of questionable quality, unsuited for sea water exposure. Systems of construction should not be used which are liable to subject the concrete to seepage of sea water during placing. Flooding of concrete protected by forms immediately after placing, as in the case of concrete deposited during low tide, is not objectionable provided the spreading and compacting is completed before the flooding occurs.

As previously stated, tremie concrete should not be depended upon to resist sea water unless protected by an impervious outer layer of concrete or other material. While concrete is sometimes tremied through small pipes into the restricted openings

of "composite" structures, as in the case of filling of spaces around protected piles, such practice is only justified when the concrete is considered as an inert filler. Tremie concrete can be relied upon for structural loads in "simple" structures of mass type. The size of the tremie under such circumstances is a function of the depth of water and the size of pocket to be filled. Sizes from 12 inches to 18 inches are recommended, the latter size for depths of 50 feet and tremie charges of 10 cubic yards.

In placing tremie concrete in sea water continuous operation is of the greatest importance. Interruption of flow, even when the charge is not lost, tends to produce laitance streaks in the concrete. When practicable, storage hoppers should be provided of such capacity that the entire pocket can be charged at one operation. Continuous flow from the accumulated concrete of the storage hopper is preferable to depositing by separate batches, with the possibility of interruption between batches. The principal use of tremie concrete in sea water work should be for sealing the bottom of walls or foundation units preparatory to unwatering.

The above precautions in manipulation, cited for "simple" concrete structures, are of still greater importance for "composite" structures encasing steel or timber. The reduction by disintegration of the small sections used in these latter structures is not only more serious in weakening the structural stability of the concrete, but it also exposes protected members of steel or wood, upon which the structural stability frequently depends, to rapid destruction by corrosion or marine borer action. Because of smaller sections and more constricted openings, a more flowable consistency must be employed and consequently the proportion of cement is increased, as previously noted. A mushy consistency which will hold the aggregate together without separation during transportation and will flatten into a plastic mass with the tamping specified is satisfactory. Systems of precasting are advantageous because of the better facilities for depositing and tamping the concrete, and of greater accessibility for inspecting and painting exposed surfaces. Systems of casting composite members in place will give good results if special precautions are taken to exclude sea water and to tamp the concrete, but owing to the difficulty of the work and its cost these precautions are frequently neglected under the stress of working conditions.

Protection of Embedded Steel and Wood

The principal cause for the disintegration of composite structures composed of concrete and reinforcing or structural steel is the rusting of the embedded steel under the accelerated corrosive action of the sea water. This rusting takes place above mean tide elevation, in that portion of the structure exposed to both sea water moisture and air. The action is increased by the use of porous concrete and by the formation of fine cracks under impact and tension, which assist the penetration of moisture and air; it is retarded and prevented by the use of dense, impervious concrete and by the sealing of cracks, to prevent or retard penetration. The action varies widely with the nature of exposure, being very rapid in "ocean" structures which are repeatedly bathed with spray, and comparatively slow in "harbor" structures which are infrequently wet directly by spray. The damage consists in the splitting and cracking of the protective coating as the embedded steel expands on rusting. The force of expansion increases with the size of bars and their concentration, and for this reason the spacing and depth of protective coating should be made dependent on the size of bar. Because the cracking destroys adhesion between the steel and concrete, mechanical bond bars are preferable to plain bars. Embedded structural steel may be protected by giving it a heavy coat of paint, so that the salt moisture cannot come in contact with the steel, but this decreases the bond. It is possible that a system of

painting reinforcing steel which will not seriously reduce the bond may be developed; but with present experience galvanizing is recommended. The protective concrete coating for painted structural steel and timber should be reinforced against impacts, with a galvanized wire mesh.

Reinforced structures having a "harbor" exposure begin to show cracks in the more vulnerable locations in from five to ten years. Many have been in service in San Francisco Bay for from 10 to 15 years without serious failure resulting from the cracking. Painting the exposed surfaces with asphalt, as specified, and maintaining the coating when it deteriorates will prolong the life of these structures so markedly as to make them comparable to high class structural steel construction which is maintained in a similar way by inspection and painting. Various modifications of asphalt are being tried by harbor engineers and may result in increased efficiency.

Intelligent design can also prolong the life of such structures, by substituting slabs, arches and smooth surfaces for articulated rectangular members and tee beam construction, which is characterized by high concentrations of steel in webs and rectangles. Adequate bracing to prevent intensive strains on rectangular frames and connections under the impact of vessels will increase durability by reducing the formation of tension cracks.

Encased structural steel construction painted with red lead and graphite on the steel and with asphalt on the surface of the concrete should be more durable than reinforcing steel construction. In San Francisco Bay much of the concrete encased steel construction now showing cracks was installed when the concrete itself was considered a complete protection and the steel was consequently not painted. The paint coats mentioned have been specified because they are standard products which have proved satisfactory on San Francisco Harbor structures. It is possible that other equally satisfactory coatings may be substituted. For the asphalt coating, it is suggested that suitable coatings of coal gas tar or water gas tar may prove effective in excluding air and moisture. Prepared hydrocarbon paints have not proved effective for this purpose, probably because they contain excessive quantities of volatiles, which leave the coating porous on evaporation. Coatings applied to embedded steel should also serve to inhibit corrosion in case the concrete absorbs sea water salts. Of medium-priced pigments which are inhibitors, red lead has proved satisfactory for structural steel in sea water exposure. Because it reduces the bond, red lead is not satisfactory for painting reinforcing steel. The question of a satisfactory coating for this purpose is still in the experimental stage and merits the attention and study of engineers.

Concrete encased wooden piles when properly constructed have proved a satisfactory type in "harbor" exposed structures. However, methods of concreting the piles in place in the water have not given as satisfactory results on San Francisco Bay as have those using pre-cast concrete casings, chiefly because of the difficulty of placing and tamping the concrete and of preventing contact with the sea water. In piles of this type the steel reinforcement is reduced to mesh or small bars so that disintegration of concrete from rusting is minimized. Under conditions requiring excessively long piles, with consequent great weight and heavy reinforcement, the jacketed pile presents advantages not only in durability but also in reducing dead loads and in decreasing cost of construction.

"Composite" structures having an "ocean" exposure deteriorate rapidly above the tide line, even when constructed of high grade concrete. This is probably due to the heavy impacts of waves, which open cracks to the steel, combined with concentration of sea salts from repeated drenchings with sea spray.

Asphalt coatings, as described previously for harbor exposures, will undoubtedly be beneficial in prolonging the life of these structures; but owing to the severity of wave wash and the cutting action of sand, it is believed that more resistant coatings are justified. Steel shell protection from low water to the deck line is suggested as a feasible protection for this exposure. Steel jackets of $\frac{3}{16}$-inch boiler plate have been in service on San Francisco Harbor for twenty-five years and similar shells of $\frac{3}{16}$-inch or $\frac{1}{4}$-inch material should give serviceable, if not equally long, life in "ocean" wharves. Concrete encased piles having a minimum of steel to rust are also advantageous under conditions of severe corrosion action. The decks should be so designed as to thoroughly brace the structure. Steel jacketed piles, either of solid concrete or composite construction, painted structural steel members encased in concrete, and galvanized or painted reinforcing bars of small dimension are suitable structural components for "ocean" wharves, considered from the viewpoint of corrosion and deterioration. There are, of course, ocean locations where the shock of waves and the shifting of bottoms are such that no structure of a wharf type should be constructed, and failures due to such storm conditions should not be confused with failure due to sea water action on concrete, wood and steel.

Constructing and Driving Concrete Piles

The size and reinforcement of concrete piles depend upon the length of pile to be handled. The quantity of steel should be the minimum which will permit careful handling without cracking. Experience has shown that piles of square cross section should range from about 16x16 inches with four $\frac{3}{4}$-inch bars, for piles of 50 feet length or under, to 20x20 inches with six 1-inch bars for piles 100 feet in length. The specified thickness of protective concrete coating should be provided above the tide line. While circular shaped piles are preferable to rectangular shapes for resisting impacts of floating debris and the internal pressure of rusting steel, the additional form cost does not warrant their use. Rectangular piles should be rounded or bevelled at the corners. In handling, piles from 50 to 80 feet long should be evenly supported at not less than four points; piles longer than 80 feet at five or more points.

Reinforced concrete piles should be driven with a steam hammer properly cushioned by means of wood or rope set in a suitable driving cap. The hammer specified (5000 lbs. falling three feet) is a standard size which is usually available, but piles of one-to-five concrete of the quality specified will resist the heaviest driving of a 7500-lb. hammer falling 42 inches, without injury, and this size is preferable for heavy piles 80 feet or more in length. When driven in sand substrata, a water jet should be used in conjunction with the steam hammer to secure penetration. Reinforced concrete piles are subject to cracking in the portion above the water line, by reason of their rectangular shape and the heavy steel required for handling. In "harbor" exposed structures, this disintegration is confined to narrow limits just above high tide line and is readily repaired by coating with mortar or additional concrete. It can be retarded, if not entirely prevented, by coating with asphalt. In "ocean" exposed surfaces, this disintegration is serious, because of its greater extent and rapidity and the more difficult repair conditions, as previously mentioned.

Pre-cast shells for concrete jacketed piles should be designed with just enough steel to enable handling and placing without cracking and injury. The depth to which the casing should be carried depends upon the possible scour at the site from currents and future dredging. Circular shells from 18 inches to 26 inches in diameter and from 2 to 3 inches in thickness have proved satisfactory, and shells 26 inches in diameter and 65 feet in length have been successfully installed.

Only the pre-cast rectangular pile and the precast shell type of jacketed pile have been considered in this outline. These are the more conservative types and are not covered by trade names or patented processes. There are a number of proprietary types of both reinforced concrete and concrete jacketed piles which have been used successfully and have merit, while other types have proved inadequate and unsatisfactory for use in sea water. The effectiveness of these proprietary types can be measured by the requirements of the foregoing specifications.

General

The specifications here presented embody less exacting requirements, in some particulars, than have often been advocated. This is due to a conviction that, while it is admittedly possible to produce more nearly perfect concrete than that specified, the increased perfection is accompanied by a cost increased out of proportion to actual efficiency gained; furthermore, provisions requiring onerous precautions, not practicable in the field, are usually ignored, and the result is frequently a poorer quality of work than can be obtained by less exacting requirements well carried out.

These specifications are an attempt to co-ordinate cost and quality, so as to produce a concrete having the highest combined efficiency in sea water resistance and economic cost. The resulting concretes will all test from 2000 to 3000 lbs. in 28 days, the 1 to 7½ concrete having practically the same strength as the 1 to 5 when used and manipulated as specified. We have ample experience to show that such concrete is satisfactory in resisting sea water on San Francisco Bay. For the strength and quality of concrete obtained, the specifications represent an economic balance in the cost of cement, aggregate and manipulation, for San Francisco market conditions; and no increase in any of these elements of cost is likely to produce a corresponding increase in the value of concrete obtained.

On the other hand, these specifications, in other particulars, such as placement of reinforcing steel, concreting under sea water and the protection of concrete in marine structures by asphaltic or other similar paint coatings, represent requirements seldom thus far enforced by most engineers charged with marine concrete construction. In respect to these requirements, however, a very extensive aggregate experience in this Bay is conclusive that the practices specified will so greatly increase the sea water resistance and, consequently, the effective life of the resulting structures as to pay many times over for any extra cost of following the requirements involved.

In conclusion, it should be remembered that while "simple" and "composite" structures are discussed separately, for the purpose of contrasting their behavior, and "harbor" and "ocean" exposures are differentiated to emphasize the effect of varying conditions, in design and practice no distinct line of demarkation can be drawn. Between these extremes there is a wide range of practicable combination of structures and a great variation in degree of exposure. Sea water exposed structures should be designed by experienced engineers if the lowest ultimate cost is to be obtained, taking into consideration all factors of first cost, maintenance and efficiency of operation. No outline of practice, however complete, will take the place of actual experience, and important structures should not be undertaken without the service of a skilled engineer.

METAL PILES

Steel and cast and wrought iron piles have been used successfully under certain conditions for many years, particularly by the U. S. Government in military and lighthouse structures. The first installation in San Francisco Bay appears to have been in the Quartermaster's Dock at Alcatraz Island built about 1870 with cast iron

piles. These piles were 10 to 30 feet long, 12 inches outside diameter and the metal was 1 inch thick. They were all filled with concrete after driving. The longer piles were driven into the mud and the shorter piles were set on concrete bases. Between that time and 1906 a total of about 1250 cast iron or wrought iron piles were placed in government structures, and practically all of them are still in service. Some of the piles have been broken off by the shock of vessels or other causes, at the point where the braces are fastened. These were repaired by placing an iron collar around them at the break. When placed, the cost of the piles was about $1.50 per lineal foot. No information is available as to their present cost, but it would probably be around $3.00 per lineal foot. In the Service Records (Chapter IX) the available information concerning the character, location and service given by these piles is presented. It will be noted that some of them have been in service for 55 years, which is a remarkable record.

The chief advantage possessed by these piles seems to be their great durability. Below water they are reported to be practically as good as new. Above low water they have rusted to some extent, in spite of attempts to protect them with paint, but they are still serviceable. The iron bracing has rusted more rapidly and on some of the docks has been renewed several times. Among their disadvantages are: (1) high cost; (2) the need for driving them with extreme care in order that the fittings and bolt holes for the bracing may come right; (3) their tendency to break at bracing points; (4) the relatively short lengths which can be used.

CHAPTER IX

SERVICE RECORDS OF PILING IN SAN FRANCISCO BAY

By H. J. Wilson *and* C. L. Hill;
L. D. Jurs, *Chairman of Sub-Committee*

The tabulations making up this section, as has already been mentioned, represent at least 90 per cent of the approximately quarter million piles located within San Francisco Bay and tributary bay waters of sufficient brackishness to be subject to borer attack. With very few exceptions they are limited to bearing piles only, fender piles being subject to considerable mechanical damage and therefore not indicating normal conditions in respect to borer attack.

The data have been secured through the cooperation of owners and harbor engineers, together with inspections by representatives of the Committee. Considerable difficulty has been encountered in obtaining data on old structures, due to incomplete records and the loss of old records in the fire of 1906. When not totally lacking, records frequently omit critical data, such as materials used, dates of installation, or dates and particulars of subsequent repairs or of removal and redriving of piles. This has resulted in approximations as to number of piles and dates of construction in a few cases and has curtailed the record of some redriven piles. But complete physical inspections were made, either for the Committee or during the course of its study, on a great number of structures, notably those of the State Harbor Commission and the Southern Pacific Company. These are by far the largest two holders of piling structures in this region, between them controlling about 60 per cent of all the piling in place. It is believed, therefore, that the records as submitted are substantially correct.

Two points merit special notice. The first is with respect to the disastrous record of untreated wooden piling. The severity of the teredo attack upon these, in the Carquinez Strait region where most of such piling was located, is borne witness to by the fact that practically all of such piles, recorded in the 1920 service record work, had failed and disappeared by the end of the next year. The second concerns the record for creosoted piling, the large relative volume of which fairly reflects the predominance of this type of piling in these waters.

In the following tables structures are listed, so far as possible, in geographical order, beginning at the point of record farthest up the Sacramento River and progressing down-stream through the Carquinez Strait, thence southward on either side, in turn, of the connected bays. For one unacquainted with the geography of the region, this arrangement may make it somewhat more difficult to find specific structures than under an alphabetic order, but it has been adopted so as to make comparisons of different types of structures, in like waters, convenient. The order of tables corresponds to the order of discussion of each method of protection in the chapter on Marine Substructure Materials, thus simplifying reference from one section to the other. In any of the tables, for structures which show replacement or repairs of piling, the history of the replacement or repair piling may be followed by turning to the table for the kind of piling used in the replacement or repair, when that differs from the original.

It is believed that the volume of records warrants final conclusions respecting

nearly every class of piling represented. The conclusions which may be drawn from the service records compiled by the Committee are discussed, or necessarily implicit in, the treatment of each kind of piling or piling protection concerned, in the preceding Engineering Practices chapter. The comparative value lent by consecutive presentation in a single statement is believed, however, to make desirable the continuance in this place of the statement of conclusions presented in former reports of the Committee.

Fig. 55. Untreated Douglas fir pile from 16-pile dolphin at Southern Pacific Alameda Mole, driven February, 1919. Removed November, 1920, on account of destruction at mud line by *Bankia*, *Limnoria* and *Teredo*.

CONCLUSIONS BASED ON SERVICE RECORDS
(As of Year 1926)

(1) Marine borers are very active in San Francisco Bay and connected waters, and untreated piling will be destroyed in as short a time as six to eight months in places where their attack is severe. In places where attack is less severe untreated piling may last from two to four years.

(2) Copper sheathed piles have given very satisfactory service in locations where damage from abrasion and theft can be minimized. Such piles carefully prepared and handled fall into the class of best surface protections, when used under the conditions indicated, but are easily damaged by either abrasion or theft.

(3) The information secured indicates that it is reasonable to expect a life of five to ten years from paint and batten protections in more or less sheltered waters, if the work is well done. If it is not well done, if the covering is damaged by careless handling or by storm battering, or if unprotected wood is exposed by mud scour, this range of life cannot be expected.

(4) The data in hand indicate that creosoted Douglas fir piling in San Francisco Bay has given a life of 15 to 20 years under past conditions and practice. Certain piles are of authentic record from the Oakland Long Wharf which were sound when removed after a service of 29 years. Some of these, redriven, are still in serviceable use after 35 years. Poor treatment, or damage to creosoted piling by careless handling, rafting, storage or construction, will materially reduce the life which might otherwise be rendered by such piling. With improvement in these practices, which is already in evidence, it is fair to expect an increase in life up to the maximum already of record.

(5) Most of the attack on creosoted piling by marine borers, which the Committee has observed throughout this survey, appears to have begun in spots where untreated wood has been exposed by damage in handling the piles or placing the superstructure. It is urgently recommended that methods of handling creosoted piles and building structures upon them be universally adopted, by which damage to the surface of the piles may be reduced to a minimum. Gratifying improvement in this respect has taken place during recent years.

(6) Pre-cast reinforced concrete piles and pile casings have not been in use in San Francisco Bay a sufficient length of time to determine their ultimate life. A detailed examination of pre-cast concrete pile jacket structures which have been in service for 15 to 18 years shows no evidence of deterioration below high water line, and they seem capable of a long further life. Gunite coated piles have given satisfactory service for more than 12 years, with no serious deterioration. The length of life to be expected from these types of construction is largely dependent upon the quality of materials and workmanship and the skill and care with which they are employed, and any laxity in these particulars will materially shorten the length of service which may be secured.

(7) Cast-in-place concrete pile jackets may be expected to give satisfactory results if properly constructed of suitable materials and if proper regard is given to exclusion of sea water from forms. The difficulties of this type of construction, however, are of such nature that the probability of securing a maximum length of life is less than in the case of pre-cast concrete piles or pile casings.

(8) Reinforced concrete cylinders cast in open caissons have been in use since 1910. Although the average life of many earlier cylinders has been considerably shortened by construction defects, these cylinders with minor repairs still give promise of a long period of service. Similar cylinders designed and constructed in accordance

with best modern concrete practice should constitute a type of construction excelled for longevity only by solid fill or mass concrete.

(9) The selection of a type of piling or pile protection for a given structure must be made upon the basis of cost and permanence of the materials under consideration, the character of the structure and the probable need for future alterations to meet the changing requirements of commerce. When a comparatively short increase over the life of untreated wooden piling is sufficient, the surface protections will often be found economical in waters not exposed to severe storm action; if a moderately long physical life approximating the average economic life of marine structures in this harbor is desired, a good creosote treatment will provide it at the lowest annual cost, so far as present knowledge goes; where conditions warrant building for the greatest permanence, with less regard for first cost, concrete construction has shown a high value in this harbor. For the protection from further damage of wooden piles already in place and showing attack by borers, not yet severe enough to require condemnation, the concrete casing, pre-cast or poured in place, is the only means of salvage found by the Committee.

Fig. 56. Piling treated by Moran process, exposed 2 years at Georgia St. Wharf, Vallejo. Note bulging and broken battens. (*S. P. Co. Photo.*)

Fig. 57. Piling treated by Paraffine Paint process, exposed 2 years at Georgia St. Wharf, Vallejo. Same defects developing as in fig. 56. (*S. P. Co. Photo.*)

Fig. 58. Iron piling at Fort Baker.

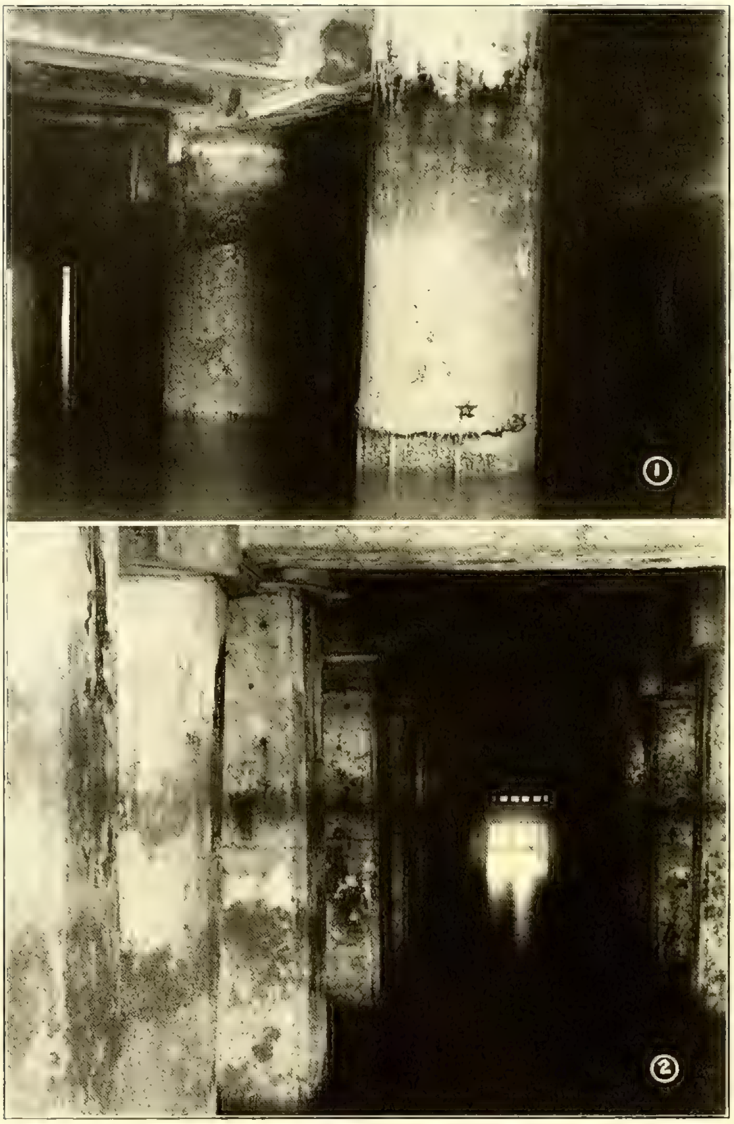

Fig. 59. (1) Reinforced concrete cylinders, Pier 28, San Francisco. Disintegration of concrete due to poor workmanship and improper tamping. These cylinders were repaired by encasing in dense concrete.
(2) Reinforced concrete piles, Pier 35, San Francisco; 6 years exposure, excellent condition.

TABLE No. 6

UNTREATED WOODEN PILES—SERVICE RECORDS TO DECEMBER 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Associated Oil Co., Avon	Wharf approach	1913	747	1—1921	Creosoted	None		Pulled for examination only.
	Wharf head	1913	179	3—1921	"	"		Structure inspected periodically.
	Wharf head	1919	393	3—1921	"	"		Wharf head will require entire replacement in 1924.
Mountain Copper Co., Martinez	Wharf and approach	1905	566	None		None		Wharf abandoned for making shipments 1920. Badly attacked.
Shell Co., Martinez	Wharf and approach	1912	Approx. 2500			321 in 1921	Pre-cast Gunite sleeves lowered into place	All untreated piles in exposed positions have been replaced with creosoted piles or protected by Gunite sleeves. (See tables 9 and 10.) Balance of piles in mud above low water.
	" "	1915		77 1920	Creosoted	None		
	" "	1918		1627—1921	"	"		
Vallejo, City of	Virginia St. Wharf	1900	300	19	Moran Piles	None		All piles driven in shallow water.
Standard Oil Co., Richmond	Point Orient Wharf	1906	670	None		All	Black's Patent Concrete Jackets	Repairs to original piles necessary after 2 years service.
Berkeley, City of	Approach to inner landing 30 Bents	1908	90	16—1914 27—1915 1—1919	Untreated	42 from 1915-1919	Concrete Jackets	No records since 1919. All subsequent repairs or replacements seem to be in the nature of minimum maintenance, to avoid collapse.
	" "	1914	16	10—1919	Untreated	1 between 1915-1919	"	No untreated piles of any value remaining in structure.
	" "	1915	27	12—1919	"	6 between 1915-1919	"	No untreated piles of any value remaining in structure.
	" "	1919	27					No records.
	Inner landing	1908	63	13—1914 3—1915	Untreated "	35 from 1915 to 1918	Concrete Jackets	
	" "	1914	13	2—1918 5—1919	" "	1 from 1915 to 1918	"	
	" "	1915	3	2—1919	"			
	" "	1918	5					No records.
	" "	1919	20					No records.
S. F.-Oakland Terminal Ry. (Now Key System Transit Co.), Oakland Pier	West Wharf Slip No. 1	1923	30					Piles driven to reinforce structure. (Subject to mechanical damage.)
	West Spring Line Slip No. 1	1923	60					
Southern Pacific Co., Oakland Estuary	Dolphin—Alameda Mole	1921	16	None		None		Eucalyptus piles. Slight surface erosion by *Limnoria*.
	Dolphin—Freight Wharf No. 1	1921	16	16	Eucalyptus	"		Original eucalyptus pile dolphin driven September, 1921. Broken by ferry boat in October, 1922. Redriven March, 1923.
Moore Shipbuilding Co., Oakland Estuary	Wharf No. 1	1920	158	None		None		Water highly contaminated by oil and discharge from adjacent gas works.
	" " 2	1920	152	"		"		
	" " 3	1920	318	277	Creosoted	"		
	" " 7	1921	512	304	"	"		Replacements made necessary by both *Teredo* and *Limnoria* action. All remaining green piles above low water.
	Marine Way No. 1							All piles cut off below mud line—330 green caps replaced in 1923 with green caps painted with creosote oil after framing.
Western Pacific Ry., Oakland	Bridge No. 721	1916	40	None		24	Gilsonite cement and burlap	Emergency repairs only.

TABLE No. 7

METAL-COVERED WOODEN PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Standard Oil Co., Richmond.	Refinery outside Long Wharf and approach..............	1903-04	775	None	... ..	All	Black's Patent concrete jacket	Heavy saturated felt and 16 oz. copper closely nailed. Repaired after 4 years service. See tables 9 and 10.
	Refinery inside Long Wharf and approach..................	1905	340	"	....	"	"	Covered with copper and saturated felt. Repaired after 3 years service.
U. S. Army, Alcatraz Island	Pier No. 1.	1870	69	16	Creosoted	All in 1907	Concrete Sheath	Original piles copper covered. See table 9 for further data.
Northwestern Pacific R. R., Tiburon.	Schooner Wharf	Unknown	174	Total unknown	Creosoted	Unknown	.	Age, kind and condition of old piles unknown. Copper covered apparently.
				39 in 1922	....	"	....	Remaining piles in very poor condition.
	Freight Slip..................	"	287	Unknown	....	"	....	In some cases completely severed.
	Passenger Slip	"	328	"				

TABLE No. 8

PAINT AND BATTEN PROTECTIVE COATINGS ON WOODEN PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Grangers Business Association, Eckley	Wharf	1920-21	2994	None	....	None	....	G. & S. Preservative paint, burlap and redwood battens. Apparently in good condition. Wharf is low and well protected from sun.
Vallejo, City of	Virginia St. Wharf	1922	26	None	....	None	....	Moran process. Battens are bulging.
Southern Pacific Co., Vallejo	Georgia St. Wharf	1921	102	None	....	None	....	Moran process. 50 piles have battens bulged by barnacles working underneath and forcing battens out. Borer attack started. 32 piles have battens broken out and borer attack started. 20 piles in good condition. (Figs. 38, 56.)
	" "	1921	89	"	....	"	....	Paraffine process. 46 piles have battens bulged. No borer attack to date because piles have layer of P. & B. paper which is still intact. When paper breaks, untreated wood will be exposed to borer action. 43 piles in good condition. (Figs. 39, 57.)
U. S. Navy, Mare Island	Causeway	1921	13	None	....	None		"Quebracho" Paint
	Dike No. 12	1920-21	301	12	Creosoted	....	....	Entire dike repaired by rip-rapping. All piles badly affected by *Teredo* at mud line. Original piles "Quebracho" paint.
	Ammunition Pier No. 1	1921	66	....	....	....	....	"Quebracho" Paint treatment. All piles in very poor condition.
S. F.-Oakland Terminal R. R. (Now Key System Transit Co.)	Old Trestle	1914	Not known	41	Creosoted	None	....	Columbia paint piles—destroyed by Limnoria.
	Short Signal Bridge N. Side of Terminal Bridge	1909	"	9	"	"	....	Paraffine Paint.
	Govt. boat landing S. Side of Terminal	1909	"	3	"	"	....	Paraffine Paint.
	3rd Row, West Spring Line Slip No. 2	1923	50	....	....	....	....	Columbia Paint Piles driven in 1923 to reinforce structure.
	Dolphins	1914	120	....	....	....	....	Additional piles driven 1923 to reinforce dolphins, weakened by *Limnoria*.
	Dolphins	1923	100	....	....	....	....	
	Spillway of riprapped trestle S.F.-Oak. Term. R. R. to Union Const.	1918	64	None	....	None	....	Columbia paint piles. Life estimated at 7 years.
Union Construction Co., Oakland	Fitting out wharf	1918	550	....	....	None	....	Columbia paint piles. All piles show varying degrees of failure. Battens are bulged, in some cases completely gone, and borer attack is well established. Scattering untreated piles have been driven to brace structures temporarily.
	Wharf No. 1	"	80	....	....	"	....	
	" 2	"	80	....	....	"	....	
	" 3	"	80	....	....	"	....	
	" 4	"	80	....	....	"	....	
	" 5	"	80	....	....	"		
	" 1	1920	30	....	....	"	....	Standard Oil Co. Bitulastic cement.
	" 2	"	30	....	....	"	....	All piles in same general condition as Columbia paint piles.
	" 3	"	30	....	....	"	....	" " "
	" 4	"	30	....	....	"	....	" " "
	" 5	"	25	....	....	"	....	" " "
Northwestern Pac. R. R., Petaluma Creek	Black Point Trestle	1920	252	None	....	None	....	Paraffine Paint piles.
Western Pac. R. R., Oakland	Bridge No. 721	1921	24	None	....	None	....	Gilsonite cement and burlap. Treatment recommended for limited life.

TABLE No. 9

CREOSOTED WOODEN PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Shell Co., Martinez	Wharf head	1921	1500 piles driven during 1921-22 exact distribution unknown	None		None		Replaced untreated fir piles. Horizontal fender line of untreated eucalyptus placed between tides. Damaged by abrasion only.
	Trestle approach, wharf head to	1920	77	"		"		Replaced untreated fir piles.
	barge wharf	1921	127	"		"		Replaced untreated fir piles.
Associated Oil Co., Port Costa	Wharf	1920	166	None		None		Replaced untreated fir piles.
	Wharf	1921	221	"		"		Replaced untreated fir piles.
Southern Pacific Co.								
Vallejo Junction	Ferry Slip and Wharf	1920-21	309	None		None		All in good condition.
South Vallejo	Ferry Slip and Wharf	1920-21	572	"		"		" "
Benicia	Car Slip	1913-14	373	"		"		" "
Benicia	" "	1920-21-22	1505	"		"		" "
Port Costa	" "	1913-14	777	"		"		" "
Port Costa	" "	1920-21	1330	"		"		" "
U. S. Arsenal, Benicia	Arsenal Wharf	1921	99	None		None		Replaced untreated fir. Present condition good.
California Wharf & Warehouse Co., Port Costa	Wharf	1920	638	None		None		All deep water piles creosoted.
U. S. Navy, Mare Island	Pier No. 3	1921	261	None		None		9 piles added to structure in 1923.
	Causeway	1921	702	"		"		
	Ammunition Pier No. 1	1921	398	"		"		
	Finger piers south of Causeway	1923	100					Driven 1923 to replace untreated fir. 2 piers rebuilt—6 demolished.
Union Oil Co., Oleum	Wharf "A" and approach	1920	978	None		None		Original untreated pile wharf collapsed October, 1919. (See fig. 1) Present condition good.
	Berths 3, 4, 5 and 6, inc. appch.	1920	810	"		"		
	Wharf "E"	1921	61	"		"		
Standard Oil Co., Richmond	Refinery outside long wharf and approach	1917	Approx. 300	None		None		
	Refinery outside long wharf	1919	400	"		"		14 additional creosoted piles driven in 1923 to replace defective Black's Patent piles.
	Refinery long wharf, middle wharf	1923	117					3 piles driven in each bent to reinforce old structure (Black's Patent).
Point Orient	Wharf and approach	1923	36					Replaced Black's Patent concrete jacket.
S. F.-Oakland Terminal Rys. (Now Key System Transit Co.), Oakland Mole	Tracks 1, 2 and 3	1912-13	261	None		None		38 additional piles driven 1923 to reinforce structure.
	Train Shed	1923	38					
	Train Shed	1913-14	293	None		None		
	Side Wharves	1913-14	837	"		"		
	Wharf No. 1							30 additional piles driven 1923 to reinforce structure.
	" " 2			43	Creosoted			Replaced bearing piles broken by vessel.
	" " 2							18 additional creosoted piles driven 1923 to reinforce structure.
U. S. Engineers, Goat Island	Torpedo Wharf	1911	66	None		None		No rigid inspection made recently. Structure apparently in good condition.
	Torpedo Wharf	1913	33	"		"		
Moore Shipbuilding Co., Oakland Estuary	Wharf No. 3	1922	273	4	Creosoted	None		Replacements made necessary by mechanical damage.
	" " 4	1921	530	None		"		All piles in good condition.
	" " 5	1921	320	"		"		" "
	" " 6	1921	300	"		"		" "
	" " 7	1923	304	"		"		Replaced untreated piles driven in 1921.
Oakland, City of	Clay St. Wharf	Not known	140	19	Creosoted	None		Wharf enlarged 1917.
	Clay St. Extension	1917	311	None		"		
Western Pacific R. R., Oakland	Dolphin Oakland Terminal	1909	38	38	Creosoted	None		No. 10 treatment.
		1921	38	None		"		No. 12 treatment.

TABLE No. 9—*Continued*

CREOSOTED WOODEN PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Howard Co., Oakland Estuary	Bulkhead wharf	July-Oct. 1917	130	None		None		Untreated fender piles badly attacked by *Teredo* and *Limnoria*. All creosoted piles in excellent condition. Replacements necessary on account of mechanical damage and poor original workmanship.
	Wharf No. 1	Oct. 1917	388	158	Creosoted	"		
	Wharf No. 2	Oct. 1917	790	63	"	"		
Hunt-Hatch & Co. (L. M. Hoefler, Owner) Oakland Estuary	Dock No. 1 foot Webster St.	1916?	Approx. 200	None		None		Apparently in perfect condition.
	Dock No. 2	1895-1900	Approx. 215	Not known		179	Sewer tile casing filled with concrete and forced down into mud about 2 feet.	Original piles creosoted. Piles have been repaired as damage became evident. First repairs made in 1916. Practically all damage traced to dog holes and abrasion.
Alameda County	Bay Farm Island Bridge Center Pier	1902	49	3—1914 42—1921	Creosoted "			
Southern Pacific Co., Oakland	Broadway Ferry Slip	1889	277	57—1923	Creosoted	None		Renewals caused by borer action and unusual wear and tear. Balance slightly attacked but still serviceable.
	Broadway Ferry Slip	1921	154	None		"		All in good condition.
Oakland Pier	Automobile Ferry Slip	1898	300	"		"		Portion of Old Long Wharf (300 piles) used in creation of new Auto Slip.
	Automobile Ferry Slip	1921	404	117—1923	Creosoted	"		404 original piles were redriven from Old Long Wharf. Renewals caused by unusual wear and tear in north wing of slip. Slight borer action on old piles.
	Passenger Ferry Slip	1898	1915	43—1923	"	"		Renewals caused by borer action.
		1921-22	369	None		"		All in good condition.
	Freight Ferry Slip	1905	535	20—1923	Creosoted	"		Renewals caused by borer action.
	" " "	1922	67	None		"		All apparently in good condition.
	Freight Wharf No. 1	1918	1512	"		"		" " "
	" " " 2	1919	871	"		"		" " "
	" " " 2	1921	260	"		"		" " "
	" " " 3	1919	1017	"		"		" " "
Oakland	Slips and ways, Peralta St.	1896	1338	68—1923	Creosoted	"		Various renewals of 1896 piles are shown in later dates.
		1903	330			"		Renewals caused by borer action.
		1905	266			"		" "
		1918	213	None		"		All apparently in good condition.
		1921	262	"		"		" " "
Alameda Pier	Ferry Slip	1903	1313	150—1916	Creosoted	"		
Mission Bay	Car slip	1904	370	270—1917	"	"		All in good condition.
Dumbarton	Trestle	1908	2571	None		1104	Concrete casing	68 unprotected piles attacked by borers.
U. S. Army, Fort McDowell	Q. M. Wharf	1903	31	No record	Creosoted	No record		Replacements to fender line required on account of breakage 60%, of borers 40%.
Fort Barry	Wharf	1900	156	"	"	"		Wharf demolished by storm June, 1922.
Fort Baker	Engineers Wharf	1888	66	"	"	"		Wharf not used in recent years.
Fort Winfield Scott	Torpedo Wharf	1908	147	"	"	"		
Golden Gate Ferry Co. San Francisco	Wharf for Ferry Slip	1922	72	None		None		
Sausalito	" " "	1922	224	"		"		
Northwestern Pacific R. R., Sausalito	East Pier	1922	19	None		None		New work to strengthen structure.
	" "	Unknown	544	Unknown		Unknown		Age, kind and condition of old piles unknown. Probably creosoted.
	Center Pier	"	245	"		"		" " "
	West Pier	"	132	"		"		" " "
Tiburon	Schooner Wharf	1922	39	None		None		New work to strengthen structure.

TABLE No. 9—*Continued*

CREOSOTED WOODEN PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Board of State Harbor Commissioners San Francisco	Pier 14	1914	1557	None	...	481 holes	Cemented	Repaired 1921, cementing dog holes attacked by *Limnoria*.
	" 16	1915	1381	"	...	289 holes	"	" " "
	" 18	1915	1381	"	...	190 holes	"	" " "
	" 20 (Track)	1912	84	19	...	None	...	
	" 22	1915	658	None	...	136 holes	Cemented	" " "
	" 24	1915	1452	"	...	386 holes	"	" " "
	" 36	1909	570	17	...	113 holes	...	" " "
	" 42	July 1918	1094	None	...	None	...	Replaced Holmes cylinder supports.
	" 44	May 1917	1057	"	...	"	...	" "
	" 46	Sept. 1914	2275	329 in 1917	Creosoted	1012	New cut-offs	Damaged by fire 1916. Replacements necessary account of fire.
	Trestle to Pier No. 46	Sept. 1914	173	None	...	None	...	
	Bulkhead Wharf Pier No. 46	Sept. 1914	179	"	...	"	...	
	" " No. 46 extension		107	"	...	"	...	
	Pier No. 7	1912	936	127	Creosoted	"	...	
	" " 9 (re-piling)	1911-15	1680	152	"	1070 holes	Cemented	Repaired 1921, cementing dog holes attacked by *Limnoria*.
	" " 11 (reconstructed)	1915	1092	None	...	340 holes	"	" " "
	" " 15	1914	1379	"	...	394 holes	"	" " "
	" " 19	1914	528	"	...	...	...	
	" " 21	1915	560	"	...	...		
	" " 23	1914	511	"	...	282 holes	Cemented	" " "
	" " 25	1914	714	16	Creosoted	455 holes	"	" " "
	" " 27 (track)	1914	573	12	"	200 holes	"	" " "
	" " 37	June 1915	2755	None	...	None	...	
	" " 41	Nov. 1914	2157	"	...	"		
	" " 43	Dec. 1914	533	"	...	"		
	" " 43 (extension)	1917	247	"	...	"		
	" " 43 (freight slips)	Dec. 1914	...	"	...	"		
	" " 43 (extension)	1919	522	"	...	"		

TABLE No. 10

CONCRETE PROTECTION ON WOODEN PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Shell Co., Martinez	Barge Wharf	1921-22	132	None		None		Pre-cast Gunite sleeves placed above water, filled with concrete and lowered into place.
	Trestle approach to barge wharf	1921-22	189	"		"		
California Wharf & Warehouse Co., Port Costa	Wharf	1921	2259	None		None		Camp process. External examination indicates concrete above low water in good condition. Concrete protected piles in comparatively shallow water.
U. S. Navy, Mare Island	Ammunition Pier	1921	133	None		None		Concrete jackets cast in place. Mud exposed at low water.
	Causeway	1921	925	"		"		
U. S. Lighthouse Service Carquinez Lighthouse	Carquinez Lighthouse	1921	110	None		None		Camp process. 4 piles pulled for examination in 1924, 3 in good condition. 1 pile destroyed by *Teredo* on account of laitance failure of concrete above mud at joint.
Standard Oil Co., Richmond	Refy. outside Long Whf. & appch.	1908	775	14+	Creosoted	None		Black's Patent concrete jacket—about 4 piles dropped out during 1923 due to defective jackets.
	" inside " "	1908	340	Few	"	"		Black's Patent concrete jackets. Condition good. Inspected 3 or 4 times annually.
Point Orient	Wharf (Inside)	1908	670	36+	"	"		Black's Patent concrete jacket. Bottom of bay scoured out below jacket. Occasional failures due to poor workmanship.
	Wharf (Outside)	1913	390	Few	"	"		Black's Patent concrete jacket. 1 pile broken in 1923 by collision. General condition good.
Berkeley, City of	30 bents of approach to inner landing	1915-1919	49	4—1919	Untreated			Concrete jackets in shallow water. Condition poor.
	" "	1915-1919	37	4—1919	"	33 in 1920	Patched with grout	Records obscure.
	" "	1919-1920	52			27 in 1920	"	Of total, 41 in extensions.
	Outer landing		245	8 fender piles	Creosoted	140 in 1920	"	Holmes single pile cylinders. (Hearsay.) Scattered piles failing throughout structure.
	Approach to outer landing	1908	230		"			Scattered piles failing.
	Inner landing			6 fender piles	"			Information questionable. Entire structure will require replacement in few years.
Howard Co., Oakland Estuary	Wharf No. 1	1917	57					Untreated piles cut off at mud line. Concrete piles cast over stumps.
U. S. Army, Alcatraz Island	Pier No. 1	1907	69	Unknown	Creosoted			Original copper covered piles installed in 1870. Repaired in 1907 by encasement in concrete sheath. Replacements made necessary by damage by boats followed by borer action.
Board of State Harbor Commissioners San Francisco	Pier No. 20	1896	120	None		None		Concrete placed in $\frac{3}{16}$-inch boiler plate shell.
	Bulkhead 26-28	1909	33	"		"		Koetitz cylinder.
	" 28-30	1909	33	"		"		" "
	Pier No. 34	1910	770	"		17—1922	Patched by Camp process	Holmes single pile.
	" 42	1906	519	519 by July, 1918	Creosoted	None		307 Holmes single pile cylinders.
	" 44	1906	519	519 by July, 1917	"	"		212 Holmes cluster cylinders. 307 Holmes single pile cylinders.
	" 5	1896	130	None	"	"		Concrete placed in $\frac{3}{16}$-inch boiler plate shell.
	" 7	1903	486	353	"	"		Holmes clusters.
	" 7	1909	50 (est.)	16	"	"		Black's Patent.
	" 11	1905	490	440	"	"		Holmes clusters.
	" 17	1911	1130	None		"		Koetitz cylinders.
	" 19	1903	234	181	Creosoted	"		Holmes clusters.
	" 21	1903	234	206	"	"		" "
	" 23	1903	234	168	"	"		" "
	" 25	1903	273	172	"	"		" "
	Fishermen's Wharf	1908-09	250	211		"		Black's Patent.
Southern Pacific Co., Dumbarton	Trestle	1923	1104	None		"		Concrete jacket over creosoted inshore piles only, placed as precaution rather than necessity.

TABLE No. 11

REINFORCED CONCRETE PILES—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
California Wine Association, Winehaven	Wharf	1919	193	None	...	None	...	
S. F.-Oakland Terminals Ry., Oakland Mole	Apron	1915	28	None	...	None	...	
U. S. Army, Fort Baker	Q. M. Wharf	1916	69	None	...	None	...	Pre-cast piles, mix 1:2:3 seasoned 4 weeks.
Board of State Harbor Commissioners San Francisco	Pier No. 1½	Mar. 1913	41	None	...	None	...	
	Pier No. 3	Mar. 1918	867	"	...	"	...	
	Bulkhead Wharf Pier No. 3	Mar. 1918	182	"	...	"	...	
	Pier No. 29	Nov. 1916	1036	"	...	"	...	
	Bulkhead Wharf Pier No. 29	Nov. 1916	282	"	...	"	...	
	Connecting Wharf Piers 29-31	1918	268	"	...	"	...	
	Bulkhead Wharf Pier No. 31	Aug. 1918	127	"	...	"	...	
	Pier No. 31	Aug. 1918	812	"	...	"	...	
	Bulkhead Wharf Pier No. 33	Feb. 1919	211	"	...	"	...	
	Pier No. 33	Feb. 1919	1061	"	...	"	...	
	Bulkhead Wharf Pier No. 37	June 1915	375	"	...	"	...	
	Bulkhead Wharf Pier No. 41	1914	257	"	...	"	...	
	Freight Slips Pier No. 43	Dec. 1914	60	"	...	"	...	
	Bulkhead No. 17	1911	135	"	...	"	...	
	Seawall No. 11A	1912	141	"	...	"	...	
	Pier No. 35	1915	2492	"	...	"	...	(See fig. 59)

TABLE No. 12

REINFORCED CONCRETE CYLINDERS PLACED IN OPEN CAISSONS—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
Board of State Harbor Commissioners San Francisco	Pier No. 29	Nov. 1916	163	None	...	None	...	Cylinders founded on untreated piles.
	" 31	Aug. 1918	124	"	...	"	...	" "
	" 39	1913	531	"	...	"	...	
	" 26	1912-13	664	"	...	188	...	
	" 28	1912-13	451	"	...	218	...	(See fig. 59)
	" 30-32	1913	1509	"	...	None	...	
	" 36	1909	427	"	...	10	...	
	" 38	1909	437	"	...	47	...	
	" 40	1909	440	"	...	51	...	
U. S. Army, Fort Mason	Transport Dock No. 1	1911	135	None	...	None	...	
	" " " 2	1911	189	"	...	"	...	
	" " " 3	1911	128	"	...	"	...	

TABLE No. 13

METAL SUPPORTS—SERVICE RECORDS TO DECEMBER, 1923

OWNER AND LOCATION	Structure	Date of Completion	No. of Bearing Piles	No. of Piles Replaced	Kind of Replacement	No. of Piles Repaired	Nature of Repairs	REMARKS
U. S. Army, Alcatraz Island	Pier No. 1	1870	145	65	12" C. I. Pipe Concrete filled	...	...	Original piles screw ends, sunk by hand power.
Fort McDowell	Q. M. Wharf	1903	60	None	...	None	...	Structure added to in 1909.
	West Garrison Wharf	1888	124	2	10" W. I. Pipe	"	...	Replacement necessitated by breakage.
Fort Baker	Q. M. Wharf	1891	54	3	"	"	...	" " (fig. 58)
S. F. Presidio	Wharf	1890	122	None	...	"	...	
Fort Mason	Wharf No. 4	1886	86	...	...	"	...	10" W. I. Piles.
U. S. Lighthouse Service, Goat Island	Lighthouse Depot Wharf	1897	93	None	...	None	...	12" lap welded pipe.

CHAPTER X

CHEMICAL INVESTIGATIONS

By W. D. Ramage *and* J. S. Burd

The work of the Chemical Sub-Committee and the Committee chemist has been confined, except for certain minor diversions, to the problems connected with the preservation of wood from marine borers. No attempt has been made to attack problems raised by the disintegration of concrete in sea water, the corrosion of reinforcing steel or various other chemical problems encountered in the general study. Within the field indicated, only those preservatives or preservative methods have been considered which involve penetration of the preservative into the wood. This has naturally resulted in centering much of the work upon coal tar creosote. The principal preservatives studied have been coal tar creosote and possible inorganic inhibitants. Furthermore, since experience has shown that properly creosoted piling is very resistant to borer attack, no treatments have been studied which might be expected to cost much more than a good creosote treatment. Outside the field indicated, some work was done in studying the effects of chlorine on marine borers.

The Committee chemist also spent some time cooperating with its biologists in a study of certain physicochemical factors in San Francisco Bay having a possible bearing on the distribution and spread of marine borers. The results of this work are presented in the Biological Section.

Free use was made throughout the chemical work of the literature of the subject (now listed in the bibliography on marine borers compiled by Dr. A. L. Barrows of the National Research Council).[1] It is believed that those familiar with the field will recognize readily how many of our data are new and how many only confirm the previous findings of others, even though the confusion due to the large amount of overlapping publications in this field may have led to obscuring or omission of credit. Particular reference should be made to the numerous studies of E. Bateman, of the U. S. Forest Products Laboratory, and of L. F. Shackell with the U. S. Bureau of Fisheries, especially on the subject of toxicity (Proc. Amer. Wood Pres. Assn., 1915, 232). The chemical investigative work of this Committee was concluded before the publication of the work of any other of the organized attacks upon similar problems pursued within the same period, and most unfortunately long before the present publication.

CREOSOTE STUDY

Observations of Test Pieces Treated With Various Creosote Fractions

The test timbers used in these experiments were 2″x4″x48″. Half of them were Douglas fir and the remainder were redwood, as indicated in table 16. As far as possible they were of sapwood and free from large knots and defects. These species are both more or less refractory to impregnation. All the test pieces were treated to refusal, by the standard vacuum-pressure method for impregnating marine piling with creosote.

[1]Marine Structures: Their Deterioration and Preservation. Report of Committee on Marine Piling Investigations, National Research Council, 1924.

In commercial treating practice varying impregnations often result from substantially uniform treating procedure, due to differences in the penetrability of different wood species or specimens used, or to varying viscosities of different oils or fractions. This is, however, largely a function of the time factor, as well as of temperature and pressure, and can be practically overcome, as it was in our experimental work, whenever minimum treating time is not a requisite. On account of the small size of the test pieces there was practically no core of untreated wood. The amount of creosote remaining in all the test pieces was about 15 pounds per cubic foot, except in the case of impregnation with fraction D (see table 14). Here some difficulty was experienced, but a reasonably satisfactory treatment was finally secured, which was approximately 10 pounds per cubic foot.

After treatment the pieces were made up into gates, each holding eight pieces, corresponding to eight different treatments. An untreated bait piece was then attached to each treated piece. Since there were 16 treatments, two such gates constitute a complete series. One complete series of treatments was immersed at each of four stations on the Bay: Southern Pacific Oakland Pier, July-August, 1921; San Francisco Pier 7, August, 1921; Crockett, July-August, 1921; Mare Island, September, 1921.

Five, and in some cases six, pieces were subjected to the same treatment. This gave one piece with each treatment for each of the four stations, and one or two for laboratory use. The 16 treatments were organized according to the following table:

TABLE 14

TREATMENTS USED ON TEST PIECES EXPOSED IN LARGE CREOSOTED GATES

1. Whole creosote oil.
2. Fraction A (210° C.-235° C.).
3. Fraction B (235° C.-315° C.).
4. Fraction C (315° C.-355° C.).
5. Fraction D (Residue above 355° C.).
6. Fraction D (Repeated).
7. Whole oil plus fraction A.
8. Whole oil plus fraction B.
9. Whole oil plus fraction C.
10. Whole oil plus fraction D.
11. Whole oil minus fraction A.
12. Whole oil minus fraction B.
13. Whole oil minus fraction C.
14. Whole oil minus fraction D.
15. Whole oil minus tar acids.
16. Oil tar distillate.

These oils were synthesized so that the several fractions were added or subtracted in the proportions in which they occurred in the whole oil, which were the following:

Fraction 210° C.-235° C.	10%
Fraction 235° C.-315° C.	40%
Fraction 315° C.-355° C.	23%
Residue above 355° C.	27%

In view of the difficulties incident to obtaining clear-cut separation by fractional distillation, and consequently to obtaining clearly marked differences in inhibitive

or destructive effects upon living organisms, it was felt that the doubling of effect gained by both adding and subtracting the required fraction might increase the decisiveness of the results.

An analysis was made of the oil from each run, as well as of that extracted from one of the test pieces after treatment. The analysis of oils soon after treatment are of no particular significance and are not given.

After planting, the gates were inspected from time to time for signs of borer attack. The bait pieces were, in all cases, heavily attacked, and in some cases were completely destroyed and had to be replaced. However, no direct attack was found on the treated wood until January 1924, after an exposure of two and one-half years. At this time, slight *Limnoria* attack was discovered on two of the pieces in the gates at Oakland Mole. These two were the pieces treated, respectively, with fraction B and fraction D. The attack was not yet severe enough so that these pieces could be said to have completely failed. Furthermore, the same treatments at the other stations were not attacked. It is possible that these pieces were not as well treated as some of the others.

At the time of this inspection, 10-inch lengths were cut from the test pieces and the oils were extracted and analyzed. The results are given in table 16. They show nothing unexpected, with the exception of an apparent relation between the physical character of the extracted oil and the percentage of tar acids remaining in the oil. Where the extracted oil contains a large proportion of solids, a greater percentage of the original tar acids remains in the oil. This is probably due to two causes. First, an oil containing a large amount of solid matter offers a smaller effective leaching surface to the water, since it prevents, to some extent, penetration of water. Second, the oils containing the larger amounts of solids are usually the higher boiling fractions, and naturally contain higher boiling tar acids, which are less subject to leaching. table 15 shows the relation between the amount of solids in the oil and the loss of tar acids.

TABLE 15

RELATIONS BETWEEN LOSS OF TAR ACIDS AND PHYSICAL CHARACTER OF CREOSOTE OIL

Tar Acids	Amount of Solids in Oil at Room Temperature											
	Small	Medium					Large	Solid				
Original per cent	5.8	7.5	6.0	4.6	5.9	6.6	6.4	6.0	4.0	6.6	6.0	5.1
Final per cent	3.0	3.9	3.8	3.5	3.2	3.1	4.6	5.4	2.8	5.2	4.5	4.4
Difference	2.8	3.6	2.2	1.1	2.7	3.5	1.8	0.6	1.2	1.4	1.5	0.7
Per cent loss of original tar acids	48	48	37	24	46	53	28	10	30	21	25	14

In considering table 16 further, it is evident that there is a very considerable loss of tar acids in all cases. This is not surprising when we find that there remains in the wood practically nothing distilling below 235° C., and that a considerable proportion of the tar acids ordinarily present distils below that point. Since these very low boiling tar acids have no permanent value, it seems evident that the usual specification for tar acids can be considerably reduced, if it is limited to those distilling above 235° C. In fact, it is the belief of the present authors that the percentage of

all constituents distilling below 235° C. should be as small as the requirements for satisfactory penetration will allow.

The loss of low boiling fractions, as shown in table 16, is, of course, accompanied by a corresponding percentage of increase in the higher boiling fractions remaining. Furthermore, calculation of the amount of oil originally and finally in the test pieces indicates that the loss falls almost entirely on these low fractions—that is, that there is no washing-out effect on the whole oil.

Inspections on these pieces continued to the following dates at the respective stations: Mare Island, January, 1924; Pier 7, San Francisco, July, 1924; Oakland Mole, October, 1924; Crockett, November, 1925. No attack was noted on any of the pieces, except those treated with fractions B, C and D at Oakland Mole. These had been slightly eroded by *Limnoria*.

It is interesting to note that no specimen treated in our work with whole creosote was directly attacked, i. e., without having in physical contact untreated wood upon which attack first started and through which it proceeded to the treated wood. Furthermore, two of the oils which stood up contained no low boiling tar acids. These are the whole creosote minus tar acids, and a sample of oil tar distillate. There are undoubtedly some tar bases, sulphur compounds, and other possibly toxic constituents in these oils; but since by far the larger proportion of coal tar creosote consists of aromatic hydrocarbons, it seems probable that these bodies must, themselves, be responsible for a large part of the preservative value of the oils.

The oil tar distillate apparently has a somewhat greater protective value than that with which it has ordinarily been credited. With sufficiently rigid specifications, it might apparently be used to some extent as a substitute for coal tar creosote, as in localities where conditions are not particularly favorable to the borers, or in mixture with it for greater safety. This result, however, is not conclusive without some further study.

Although no direct attack of any consequence was found on the creosoted pieces, attack was perceptibly heavier where the borers went from the bait pieces into the treated pieces. An inspection of the creosoted gates at Pier 7, San Francisco, made on April 12, 1923, disclosed no evidence of direct attack on any of the treated pieces, even though the bait pieces attached to them had been heavily attacked by *Bankia* and, in all but one case, almost eaten away by *Limnoria*. However, in every piece but one, the *Bankia* had gone through from the untreated bait pieces into the treated pieces. In some cases, the penetration of the borers into the treated pieces was slight, but in other cases they had penetrated several inches. In several pieces where a large number of borers had nicked the treated wood, none had gone in far. That the borers showed some reluctance to entering the creosote is shown by the deflection of the burrows in the bait pieces as they approached the treated wood (fig. 22). In some cases, they ceased boring and sealed off their burrows rather than enter the creosoted wood. The amount of crowding existing in the bait pieces apparently has a considerable effect on the number of borers trying to enter adjacent treated wood, since the only treated piece which showed no attack was the one with the least crowded bait piece. Table 17 gives the complete description of these pieces at the time of inspection. There was no *Limnoria* attack on any of the treated pieces. The data are not extensive enough to warrant any final conclusion, but it seems reasonable to attribute a high protective power to a treatment into which a large number of borers have started to penetrate from the bait piece, if none of these borers penetrate to any depth. On this basis, every fraction of the creosote shows a considerable protective value.

The foregoing emphasizes the importance of avoiding untreated braces or other

TABLE No. 16

COMPARISON OF OILS USED IN TIMBER TREATMENTS WITH OILS EXTRACTED AFTER 2½ YEARS IN THE WATER

No.	Date of Treatment	Date of Immersion	Kind of Wood	Treatment	Analysis of Oil in Per Cent: Below 210° C.	210 to 235°	235 to 270°	270 to 315°	315 to 355°	Residue above 355° C.	Specific Gravity	Tar Acids	Amount Solids in the Oil at Room Temp.
1	6- 8-21	7- 7-21	Douglas Fir	Whole Oil	0.1 0.1	4.2 1.2	24.6 6.1	18.0 20.2	20.3 29.7	32.5 42.6	1.090 1.098	7.5 3.9	.... Medium
2	6- 9-21	7- 7-21	Douglas Fir	Fraction A 210-235° C.	44.0 Not enoug	34.3 h oil for anal	12.1 ysis in samp	5.1 le taken.	4.1%	above 315°	1.006	14.3	.... Large
3	6-10-21	7- 7-21	Douglas Fir	Fraction B 235-315° C.	0.0 0.1	22.6 2.4	40.9 44.4	24.1 31.1	11.1% 22.7%	above 315° above 315°	1.041 1.048	5.8 3.0	.... Small
4	6-11-21	7- 7-21	Douglas Fir	Fraction C 315-355° C.	0.0 0.0	0.0 0.0	0.0 0.8	16.3 12.3	56.2 54.0	27.0 32.9	1.108 1.112	6.0 5.4	.... Solid
5	6-12-21	7- 7-21	Douglas Fir	Fraction D Res. above 355°	Poor pen	etration.	Repeated i	n next run.					. . . .
6	6-30-21	8- 4-21	Redwood	Fraction D Repeated	4.1% 4.0%	below 355° below 355°	C. C.			95.9 96.0	1.180 1.182	4.0 2.8	.... Solid
7	7- 1-21	8- 4-21	Redwood	Whole Oil +Fraction A	0.0 0.0	6.9 2.3	27.7 15.2	16.7 19.3	20.6 19.0	28.7 43.8	1.076 1.088	6.4 4.6	.... Large
8	6-16-21	7- 7-21	Douglas Fir	Whole Oil +Fraction B	0.0 0.0	3.0 0.8	34.0 12.1	20.2 21.0	17.4 24.3	24.8 41.6	1.080 1.099	6.0 3.8	.... Medium
9	7-6-21	8- 4-21	Redwood	Whole Oil +Fraction C	0.0 0.0	3.8 0.3	20.6 7.5	18.3 17.5	26.8 30.2	30.4 44.4	1.085 1.103	6.6 5.2	.... Solid
10	6-13-21	7- 7-21	Douglas Fir	Whole Oil +Fraction D	0.0 0.0	0.1 0.1	10.0 5.4	16.2 8.3	20.2 22.9	53.4 63.1	1.121 1.128	6.0 4.5	.... Solid
11	7- 9-21	8- 4-21	Redwood	Whole Oil −Fraction A	0.0 0.0	0.0 0.0	14.6 4.8	19.6 22.3	28.6 28.9	37.2 43.8	1.101 1.105	4.6 3.5	.... Medium
12	6-15-21	7- 7-21	Douglas Fir	Whole Oil −Fraction B	0.0 0.0	0.0 0.5	19.0 6.2	26.6 10.4	20.9 28.9	33.2 53.9	1.110 1.129	5.1 4.4	.... Solid
13	7- 7-21	8- 4-21	Redwood	Whole Oil −Fraction C	0.4 ...	17.8 3.5	19.3 13.4	12.3 17.6	10.1 10.3	39.9 50.0	1.084 1.092	5.9 3.2	.... Medium
14	7- 8-21	8- 4-21	Redwood	Whole Oil −Fraction D	0.0 0.0	8.9 2.1	28.2 8.6	22.6 29.5	30.3 36.8	10.0 22.7	1.062 1.082	6.6 3.1	.... Medium
15	7-13-21	8- 4-21	Redwood	Whole Oil −Tar Acids	0.0 0.0	0.0 1.1	21.7 3.8	19.1 22.2	24.6 28.1	34.6 44.7	1.087 1.099	0.0 0.0	.... Medium
16	7-26-21	8- 4-21	Redwood	Oil Tar Distillate	0.0 0.0	2.7 3.3	23.3 8.9	7.8 12.5	11.4 15.2	54.3 59.7	1.117 1.118	0.0 0.0	.... Solid

untreated timbers in contact with treated structures, as previously noted by Shackell and others.

TABLE 17

DESCRIPTION OF CREOSOTED TEST PIECES ATTACKED THROUGH UNTREATED BAIT PIECES

Treatment	Depth of Burrows in Treated Wood				Per cent below ¼″	Bait Pieces
	Surface nicks only	⅛″ to ¼″	½″ to 1″	More than 1″		
Whole Oil	9	3	..	1	92	H.A.*
Fraction A	15	1	..	..	100	C.D.†
Fraction B(‡)	..	..	..	..	..	H.A.‡
Fraction C	10	..	..	..	100	C.D.
Fraction D	10	2	..	..	100	C.D.
Fraction D (repeated)	35	..	..	..	100	C.D.
Whole Oil+Fraction A	140	1	..	..	100	C.D.
Whole Oil+Fraction B	25	5	4	..	88	C.D.
Whole Oil+Fraction C	12	..	3	..	80	C.D.
Whole Oil+Fraction D	25	2	..	..	100	H.A.
Whole Oil−Fraction A	45	..	4	5	83	C.D.
Whole Oil−Fraction B	30	..	9	6	67	C.D.
Whole Oil−Fraction C	13	5	1	4	78	C.D.
Whole Oil−Fraction D	75	..	7	4	87	C.D.
Whole Oil−Tar Acids	25	6	..	1	97	C.D.
Oil Tar Distillate	40	2	..	1	98	C.D.

* Heavily attacked by *Bankia* and *Limnoria*, but still holding together.
† Completely destroyed, only fragments hanging to bolts.
‡ The crowding of the borers in this bait piece was not as great as in the others.

Studies of the Extent and Character of Losses from Creosote under Various Conditions

The following small scale tests were carried out for the purpose of finding the amount and character of the loss of creosote constituents from treated wood exposed in air and in sea water. They are not intended to be regarded as service tests, since they do not quantitatively represent the losses from marine piling. They are, however, satisfactory as indicating the qualitative changes in creosote under various conditions, and to that extent they can probably be regarded safely as somewhat accelerated service tests.

For this study, ten test pieces were cut from a Douglas fir sapling. They were about 6″ in length by 5″ in diameter, and were treated to refusal with a medium weight creosote from the Republic Creosoting Company. The pieces were weighed before and after treatment to determine the weight of oil absorbed. This was very high, being from 25 to 30 pounds per cubic foot.

Two of the pieces were exposed in the air and the rest were placed in the bay. At the same time, portions of the original oil were exposed in the laboratory in open dishes. The dishes and the air pieces were weighed from time to time to determine the amount of loss. Pieces were also removed from the bay at intervals, and the oil extracted and weighed. From the weight of oil recovered and the weight initially present, the percentage of loss from these blocks can also be calculated.

Figure 60 shows the rate of loss of creosote constituents from treated wood in water, treated wood in air, and from the open dishes. All losses are corrected to the same mass of oil and same evaporation surface. Table 18 shows the comparative losses in the three cases after various elapsed times.

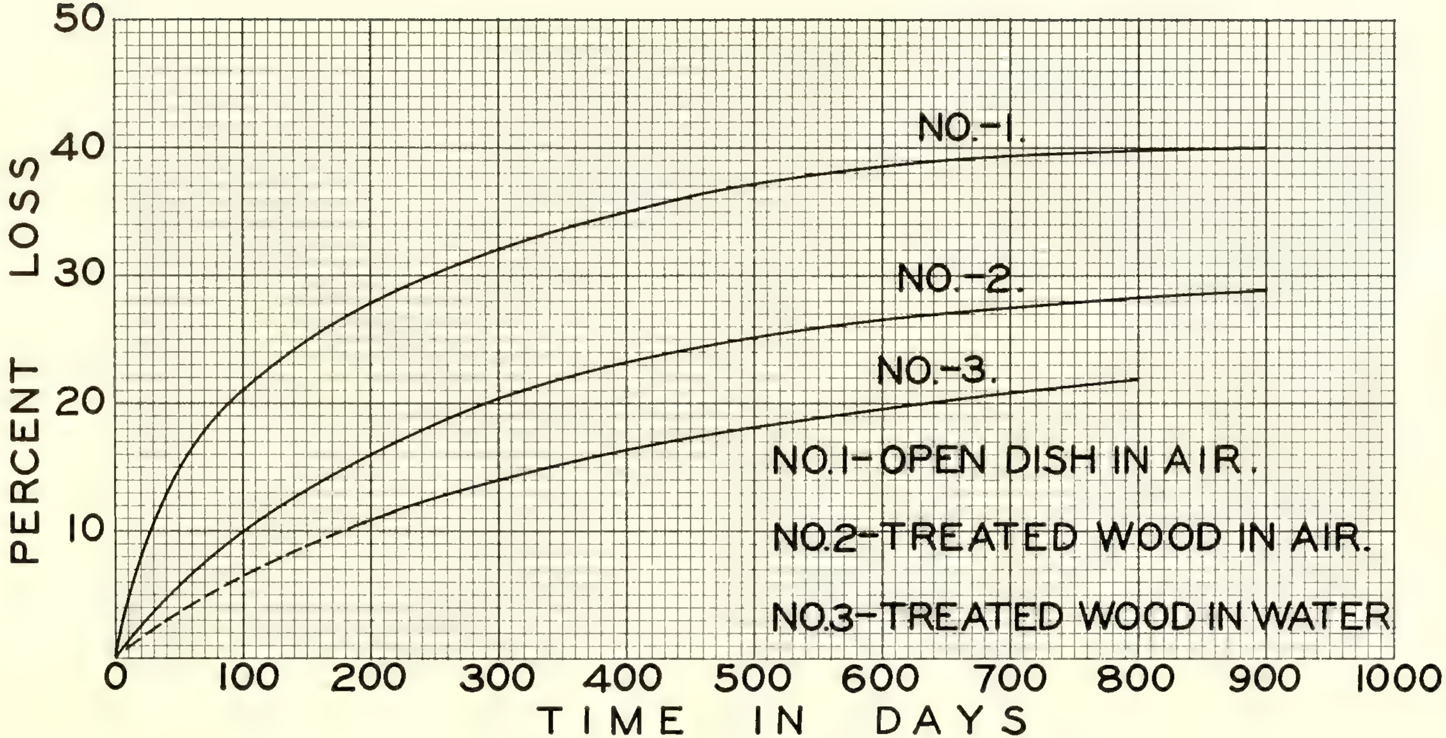

Fig. 60. Curves showing rate of loss of creosote under various conditions.

The rate of loss from treated wood in air is not nearly as great, especially at first, as would be expected on the basis of the loss from the open dish. In fact, the form of the two loss curves is different throughout their whole range and the rate of loss from treated wood reaches a fairly constant value at a much smaller percentage loss than in the case of the open dish. This indicates that the surface of the treated wood does not act as a free oil surface. However, the rate of loss from the treated surface is dependent on the rate of feeding of low boiling constituents to the surface, which would probably be considerably lower than in the free oil, merely on account of the cutting down of circulation in the oil. This is substantiated by the slightly increased amounts of low boiling constituents found as we go inward through the treated wood. If the rate of feeding to the surface were rapid, the composition of the oil should remain constant throughout the treated wood. The same slight composition differences in different layers are also shown by a thirty-year-old pile from the Oakland Long Wharf. There is also a possibility that the rate of feeding to the surface is further limited by an actual absorption of the oil by the wood, cutting down the effective vapor pressure of the oil. In either case (and particularly in the latter), the nature of the wood used would be likely to have a considerable effect upon the rate of loss.

TABLE 18

*LOSS OF CREOSOTE BY LEACHING AND EVAPORATION

Time, in days:	10	30	90	222	475	512	787
Percentage loss from open dish in air	5.0	10.1	20.0	28.9	36.7	37.4	39.6
Percentage loss from treated wood in air	1.2	3.3	7.2	16.6	24.6	25.3	28.0
Percentage loss from treated wood in sea water	....	....	....	11.6	17.5†	18.1†	21.9†

*All losses corrected to same mass of oil and same exposed surface.
†Some mechanical loss (possibly as much as 1 per cent) in sampling.

On this basis it appears that no evaporation study of free oil is of value, except, in a very general way, in determining the probable rate of loss from treated timbers.

The smaller rate of loss from treated wood in water as compared with treated wood in air indicates the advisability of storing creosoted timbers in water when possible[1]. Probably the reason for the smaller loss in water can be ascribed roughly to the greater volatility than solubility of creosote constituents in general. Also the rate of feeding to the surface is probably cut down by the swelling of the wood in water, which is not prevented by the presence of oil, because water can penetrate the cell walls of wood while creosote does not do so.

In addition to knowing the absolute loss of creosote from treated wood, it is important that we know on what constituents this loss falls. To do this, we must be able to effect complete recovery of the oil remaining in the wood, without altering its character. Experiments on the use of benzene as an extracting solvent indicate that with it the oil can be completely recovered in an unchanged condition. The Committee work had the benefit of detailed knowledge of the oils originally used in all such tests, including carefully preserved identical samples; the lack of which has invalidated, or at least cast doubt upon, most previous attempts in this direction.

[1]The advantage of water storage may be offset by the increased rate of loss of tar acids, especially if storage is for a long time.

The analysis of the original creosote and that recovered by extraction from treated wood gave practically identical results. The effect of benzene on the oil was still further tested by boiling a 50-50 mixture of benzene and oil under a reflux condenser for three hours. Benzene was then added until it was 90% of the whole and the digestion continued for ten hours more. The recovered oil was the same as the original oil, as shown in table 19, although the treatment was far more severe than in any ordinary extraction.

TABLE 19

EFFECT OF BOILING BENZENE ON CREOSOTE OIL

Distillation	Original Oil	Oil after Benzene Digestion
Up to 210° C.	0.2%	0.0*
210-230° C.	1.5%	0.7*
230-250° C.	7.2%	7.0
250-270° C.	12.8%	12.5
270-290° C.	10.7%	10.8
290-315° C.	10.4%	10.5
315-355° C.	16.1%	16.8
Residue	41.1%	41.5

*Small amount of loss in removing benzene.

TABLE 20

ANALYSES OF OILS AFTER EXPOSURE IN TREATED WOOD AND OPEN DISHES IN THE AIR

	Original Oil	Test Piece No. 1E	Open Dish No. 1	Open Dish No. 2
Time exposed	......	263 days	530 days	1005 days
Loss	......	19.4%	37.6%	41.3%
Specific Gravity	1.059	1.063	1.10–	1.103
Tar Acids	10.7%	8.0%	5.4%	3.7%
Distillation:				
Up to 210° C.	1.5%	0.0%	0.0%	0.0%
210-230° C.	9.5%	0.7%	0.0%	0.0%
230-250° C.	16.5%	5.5%	0.1%	0.1%
250-270° C.	12.6%	14.7%	0.9%	0.6%
270-290° C.	8.1%	14.4%	5.7%	1.9%
290-315° C.	8.2%	14.0%	21.1%	19.1%
315-355° C.	16.4%	18.5%	29.4%	32.8%
Residue	27.2%	32.1%	42.8%	45.1%

Table 20 gives the composition of the recovered oils after exposure for some time, in treated wood and in open dishes, in the air. Table 21 gives the results for the oil from treated wood exposed in sea water.

The composition changes found in the oil in this series of tests are practically the same as those found in the earlier experiments. The loss falls on the low boiling fractions, and a considerable portion of the tar acids is lost. The chief difference between the oils extracted from the water-exposed and air-exposed pieces lies in the percentage of tar acids. The rate of loss of tar acids from treated wood in water is greater than from treated wood in air, in spite of the fact that the rate of loss of the

TABLE 21

COMPARISON OF ORIGINAL AND EXTRACTED OILS* FROM SMALL TEST PIECES AFTER EXPOSURE IN SEA WATER

	Original oil	Test piece No. 1L	Test piece No. 2L	Test piece No. 3L	Test piece No. 4L
Time Exposed		222 days	475 days	512 days	787 days
Loss		11.6%	17.5%	18.1%	21.9%
Specific Gravity	1.059	1.063	1.067	1.066	1.067
Tar Acids	10.7%	5.7%	3.8%	3.6%	3.6%
Distillation:					
Up to 210° C.	1.5%	0.0%	0.0%	0.0%	0.0%
210-230° C.	9.5%	2.6%	1.6%	1.7%	1.2%
230-250° C.	16.5%	17.8%	10.3%	11.0%	7.8%
250-270° C.	12.6%		13.9%	13.9%	14.1%
270-290° C.	8.1%	15.9%	12.0%	11.5%	10.7%
290-315° C.	8.2%	14.5%	10.6%	12.0%	12.2%
315-355° C.	16.4%	17.8%	17.6%	16.3%	19.6%
Residue	27.2%	31.2%	33.5%	33.1%	34.2%

*The oils from the different layers of these test pieces were analyzed separately, but only the average analysis for each block is given, since the differences in composition between layers were small. There was, however, a slightly smaller amount of low boiling constituents and tar acids in the outer layers.

total oil is greater in the air. Analysis of oils extracted from piling shows similar differences in air and water sections. A typical analysis of this kind is given in table 22 for a pile pulled from the Alameda Wharf of the Associated Oil Company after four years' service.

TABLE 22

COMPARISON OF OILS EXTRACTED FROM AIR, WATER, AND MUD SECTIONS OF A PILE AFTER FOUR YEARS' SERVICE

	Original* Oil	Air Section	Water Section	Mud Section
Per Cent of Oil in Treated Wood		49.9	54.1	55.0
Specific Gravity	1.06+	1.078	1.074	1.072
Tar Acids		3.6%	3.0%	3.3%
Distillation.				
Up to 210° C.	0.0%	0.0%	0.0%	0.0%
210-235° C.	5.5%	1.1%	1.8%	1.8%
235-270° C.	23.5%	16.4%	21.5%	21.9%
270-315° C.	23.1%	26.5%	25.7%	25.9%
315-355° C.	19.3%	24.3%	21.8%	21.3%
Residue above 355° C.	28.0%	31.4%	28.8%	28.8%

*Manufacturer's Analysis.

The above results further emphasize the validity of our former conclusions that the low boiling fractions should be limited to the amount necessary for good penetration and that the tar acid specification should refer to the fractions above 235° C.

As already noted here there are slight differences in composition in the oil recovered from different layers of the treated wood. This condition, however, is apparently one which arises after treatment when an equilibrium rate of loss has been established, since studies of successive layers in recently treated piles indicate that creosote penetrates the wood in an unaltered condition. That is, with straight or whole run creosotes, there is no tendency toward filtration of the heavier constituents in the outer layers of wood.

Fixation of Creosote Constituents

It has been suggested that the low boiling fractions of creosote are not entirely lost, but that part of them polymerize or condense to higher boiling constituents, thus becoming more or less permanently fixed in the wood. Some of our earlier results seemed to indicate that this was the case. However, very careful further study of this point gave only negative results. Although all changes in composition found were in the direction to indicate polymerization, they were too small to be of any significance.

The idea has also been put forward that certain creosote constituents are fixed in the wood by an actual combination with the wood. Any such combination must be very loose, since we have shown that it is possible to recover creosote completely by a benzene extraction. Furthermore, careful analyses of the wood itself before treatment and after removal of the creosote, show no significant differences. Table 23 gives the results of these analyses.

TABLE 23

ANALYSIS OF WOOD SUBSTANCE OF DOUGLAS FIR SAPLING BEFORE AND AFTER TREATMENT WITH CREOSOTE

	*Benzene soluble extract	Alcohol soluble extract	Cellulose	Lignins	Mannan
Before Treatment...	0.20%	3.28%	56.66%	28.25%	7.39%
After Extraction....	0.21%	3.77%	55.22%	28.48%	7.61%

*All results calculated to 4.0% moisture content.

INORGANIC TREATMENTS

For many years various inorganic salts have been used in the preservation of wood. However, the only ones which have attained at all general use are zinc chloride, copper sulphate, and mercuric chloride. Even these have not been used to any great extent under high moisture conditions, on account of their large solubility and consequently rapid leaching from the wood.

The value of any treatment depends upon two factors, the immediate effectiveness of the protection afforded, and the permanence of the protection. Obviously, even though such substances as those mentioned might afford protection for a short time, they have no value for the permanent preservation of marine piling, since they would too soon be lost from the wood.

It is readily seen that the high moisture conditions to which marine piling is subjected make the preservative use of inorganic salts very difficult. Either they must be left in the wood in some very slightly soluble form, in which case their preservative value is presumably cut down, or else leaching must by some means be prevented.

The only readily apparent method for leaving inorganic salts in the wood in a soluble form and still having permanent protection is by the use of oil emulsions. All available petroleum oils are lighter than water. The formation in these oils of stable emulsions of solutions much heavier than water is a matter of some difficulty. The

only high gravity oils which are appreciably cheaper than creosote are certain oil tar distillates. Emulsions in these oils of such solutions as zinc chloride, copper sulfate, and mercuric chloride, would probably possess a considerable protective value, particularly since the oil tar distillate has been found to possess some protective power in itself.

The methods which we studied chiefly were those involving precipitation in the wood of a so-called insoluble (i.e., slightly soluble) inorganic compound. There are two main methods for doing this. The first is the method of double treatment and the second involves decomposition of the treating solution by some means after treatment.

To get satisfactory penetration and distribution of the second solution, in the double treatment method, it is necessary to dry the wood fairly well after the first treatment. In practice, we found this a matter of some difficulty, and it is probably not economically feasible on a large scale. The double treatment idea was, therefore, abandoned, excepting for our preliminary experiments.

A preliminary study of the subject was made by treating small Douglas fir blocks with various inorganic substances, including copper sulfide, arsenic sulfide, antimony sulfide, lead chloride, mercurous nitrate, mercuric sulfide, and metallic selenium. The precipitation of some of the foregoing substances in the wood involved a double treatment. As already noted, this was not thought to be feasible on a large scale. Hence, a second series of blocks was treated, using single treatment methods believed to be applicable in commercial practice. The treatments were as follows, the dry wood being impregnated with the aqueous solutions at ordinary temperatures and 90 pounds pressure:

1. *Chandler's Solution.* Solution contained 8.5% sodium carbonate (Na_2Co_3), 1.5% sodium bicarbonate ($NaHCO_3$), less than 1% copper sulfate ($CuSO_4 \cdot 5H_2O$). This solution must be used soon after preparation, since it gradually decomposes until the copper content is less than 0.5% as $CuSO_4 \cdot 5H_2O$.

    A. Impregnation in cold. No after-treatment.
    (Chandler's method.)

    B. Impregnation in cold. Steamed after treatment to precipitate cuprous oxide (Cu_2O) in the wood.

2. *Sodium selenite and sodium hydroxide* ($Na_2SeO_3 + NaOH$). Solution contained 5% selenium dioxide (SeO_2) and 0.5% free NaOH. Steamed after treatment to precipitate metallic selenium in the wood.

3. *Copper sulfate and sodium thiosulfate* ($CuSO_4 + Na_2S_2O_3$). Solution contained 5% $CuSO_4 \cdot 5H_2O$ (crystalline) and 12% $Na_2S_2O_3 \cdot 5H_2O$. Steamed after treatment to precipitate cupric sulfide (CuS) and sulfur (S) in the wood.

4. *Mercurous nitrate* ($HgNO_3$). Solution contained 1% $HgNO_3 \cdot 2H_2O$. No after treatment. Sea water precipitates calomel (HgCl) in the wood.

5. *Mercuric chloride and sodium thiosulfate* ($HgCl_2 + Na_2S_2O_3$). Solution contained 1% $HgCl_2$, 4% $Na_2S_2O_3 \cdot 5H_2O$, and 2% Na_2CO_3 (sodium carbonate). Steamed after treatment to precipitate mercuric sulfide (HgS), mercurous oxide (Hg_2O) and other decomposition products of this solution.

The foregoing treatments utilize two ideas. The first of these is the use of solutions of metallic salts, which precipitate relatively insoluble metallic compounds on heating. The second is the utilization of the reducing power of the wood in precipitating relatively insoluble metallic compounds in the wood. The latter method has not to our knowledge been used prior to the work of this Committee.

Sodium thiosulfate is useful in making up both types of solutions. An excess of sodium thiosulfate added to a solution of a heavy metallic salt, such as copper sulfate,

or mercuric chloride,[1] gives a solution which is stable for a long time at room temperature, but which decomposes on heating, giving a precipitate of the metallic sulfide and some free sulfur. Solutions of this type can also be made alkaline without the formation of any precipitate. They then fall in the second class above.

The reducing power[2] of the wood is due to the carbonyl groups in the cellulose molecule, and is active only in alkaline solutions. Since most metals precipitate in ordinary alkaline solutions, special solutions must be used such as the thiosulfate solution above.

The timber is impregnated with the alkaline solution and subsequently heated, whereupon the reducing action of the wood causes precipitation of a metallic oxide or the free metal. The heating merely serves to speed up the reaction.

Treatments Nos. 1B and 2, above, depend entirely on the reducing power of the wood. In No. 3, the decomposition depends on heat alone. Treatment No. 5 gives a decomposition which is a mixture of the two types.

Four sets of test pieces with the above treatments were placed at various stations in the bay. All showed some retardent action against borers, as compared with untreated wood, but within one season all were attacked to some extent. Some of the treatments devised may have value for other purposes, but apparently none of the inorganic treatments which we have studied have any permanent value in the protection of marine piling against borer attack. This conclusion is strengthened by the rapid failure in marine use of proprietary metallic salt preparations, such as colloidal metallic selenium and tellurium in the Protections tests of this Committee, and of mercuric chloride and oleate as tested in the East.

EFFECTS OF CHLORINE ON TEREDOS

The following experiments were carried out at the request of the National Research Council for the purpose of determining the effects of chlorine liberated in sea water upon adult teredos in their burrows, for which, as a means of practical control, apparently extravagant claims have been made upon this coast.

Three pieces of 2″ x 4″ timber infested by *Teredo navalis* were obtained from Dumbarton through the Committee biologist. One was used as a control, and was kept in fresh bay water throughout the test. The other two were exposed to various concentrations of chlorine in bay water.

The experiments extended over a period of several weeks, during which time the teredos were alternately exposed to chlorine and fresh bay water. The time of exposure to chlorine varied from 24 to 72 hours. After being exposed to chlorine, the borers were usually left for about 24 hours in fresh bay water, but in all cases observed, the activity of their siphons indicated complete recovery in a much shorter time than this.

The concentrations of chlorine possible when the gas is liberated in sea water under no pressure other than atmospheric, are necessarily very small. The initial concentrations of chlorine used in our experiments were from 30 to 120 parts per million parts of sea water. These concentrations dropped off rapidly since the containers were not gas-tight. In practically all cases, however, there was sufficient chlorine to give a distinct odor during most of the time of exposure.

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[1]In the case of the mercuric chloride, the stability of the solution is somewhat increased by the addition of a little Na_2CO_3 or NaOH.

[2]An actual determination of the reducing power of Douglas fir sapwood on Fehling's solution, gave a value of 0.14 pounds of $CuSO_4$ reduced to Cu_2O per pound of wood. The determination was made on sawdust which had been extracted with benzene and alcohol to remove all except the structural material of the wood.

In small concentrations, below 10 parts per million, or practically the point where the odor of chlorine over the solution becomes noticeable, the teredos continued to feed, seemingly unharmed. It must be remembered that in maintaining even these small concentrations of chlorine, considerable amounts will be given off into the surrounding atmosphere. At higher concentrations the siphons were always immediately withdrawn. However, after the highest concentration used (120 parts per million) applied for the longest time tried (72 hours), on the stick being placed in fresh sea water (chlorine free) the borers again extended their siphons and were apparently none the worse for their experience. This concentration of 120 parts per million was sufficient to give off into the air enough of the gas to make human breathing very uncomfortable.

Table 24 gives a summary of the experimental data. At the end of the series, the teredos in all aquaria were apparently in good health, and there were as many active siphons as at the beginning. Some of the borers lived for several months, even under the unfavorable conditions of the aquaria. The borers in one of the pieces subjected to the chlorine treatment lived longer than those in the control piece, which had had no chlorine treatment.

TABLE 24

EFFECTS OF CHLORINE ON TEREDOS IN THEIR BURROWS

	Number of exposure	Time* of exposure	Initial conc. of Cl_2	Final conc. of Cl_2	Average conc. of Cl_2	Reaction of borers	Permanent effect
	1	24 hrs.	40 p.p.m.†	< 20 p.p.m.	30 p.p.m.		
	2	24 "	50 "	20 "	35 "		
Block No. 1	3	24 "	50 "	20 "	35 "	Siphons all retracted	
	4	48 "	110 "	20 "	65 "		
	5	72 "	30 "	< 10 "	20 "		None
	1	24 hrs.	60 p.p.m.	20 p.p.m.	40 p.p.m.		
	2	24 "	80 "	30 "	55 "		
Block No. 2	3	24 "	40 "	< 20 "	30 "	Siphons all retracted	
	4	48 "	30 "	< 10 "	< 20 "		
	5	48 "	50 "	10 "	30 "		
	6	72 "	120 "	40 "	80 "		None

*After each chlorine exposure, the block was placed in fresh bay water for 24 hours.
†p.p.m. = parts per million.

Undoubtedly the chlorine was offensive to the borers. When it was added slowly, the siphons were retracted progressively along the wood in the direction in which the chlorine spread through the water. Furthermore, when the infested pieces were taken out of fresh bay water, exposed to the air for a moment and put back into the water again, the teredos extended their siphons and began to feed again after a very few minutes. On the other hand, if they were put into a solution giving a noticeable odor of chlorine, they did not extend their siphons again. They were never found feeding in concentrations as great as 10 parts per million. The concentration of chlorine used in several of the experiments might, therefore, have been toxic to the teredos,

had they not been able to close their burrows against the gas. This is one of the major premises overlooked by the promoters of chlorine extermination of marine borers.

There remains a possibility that a practically continuous maintenance of small concentrations of chlorine might prevent settling of the larvae on the piling; or that the young teredo larvae might be more sensitive to the action of the chlorine than are the adults. The results of our experiments indicate, however, the improbability that chlorine (entirely aside from its many objectionable features) could economically be maintained around piles in sufficient concentration for a sufficient length of time to kill the borers when once established, or to be of any practical value in the protection of marine piling.

SUMMARY OF CONCLUSIONS

The following is a brief summary of the conclusions reached in the preceding paper:

1st. That straight-run or whole creosotes penetrate wood in an unaltered condition; that is, that there is no tendency toward filtration of the heavier constituents in the outer layers of the wood.

2nd. That there is no fixation of creosote constituents in the wood, and that low boiling substances do not polymerize to any appreciable extent to form high boiling substances.

3rd. That the loss of creosote from treated wood is due to the combined volatility and solubility of the constituents in the low boiling fractions, and that the loss falls almost entirely on these low boiling constituents.

4th. That creosote constituents boiling below 235° C., while in general more effective as long as they remain in the wood, are largely lost from untreated wood within two or three years, therefore that the percentage of these low boiling constituents in the oil should be limited to the amount necessary for good penetration; also that the tar acid specification should refer to the fractions above 235° C.*

5th. That certain oil tar distillates have a greater protective value against marine borers than that with which they have ordinarily been credited.

6th. That inorganic substances, by themselves, have little prospect of value in the preservation of marine piling against borer attack.

7th. That chlorine treatment has no practical value in the protection of piling against marine borers.

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*The commonly available whole oils, as tested by this Committee, do not contain an excessive amount of light oils, from this point of view. The creosote specifications approved by the Committee (p. 108) provide sufficient light oils for this purpose; and whole oils meeting these requirements are available, as shown by the numerous tests of the Committee.

CHAPTER XI

EXPOSURE TESTS OF SPECIAL PROTECTION METHODS

By R. C. Miller *and* C. L. Hill

In addition to the experimental work on preservatives and methods of treatment described in the foregoing chapter, this Committee undertook to make tests of various woods reputed to have unusual natural resistance to borer attack, and of methods for protecting wooden piling, most of which have not been in use for a long enough time to make service records available. These methods are mainly, although not exclusively, of the class of paint and batten surface protections, and most of them involve materials of patented or secret composition. Their number is considerable, and the insistence with which they are being promoted in this region creates a need among users of piling for such information as can be obtained, on unprejudiced and reliable authority, for the appraisal of values.

Such tests were made usually at the request of the proponents of the methods in question. The tests have been carried out in accordance with the standard practice adopted by this Committee for its own experimental work, and every effort has been put forth to insure a fair and thorough test of each sample submitted. In some cases, however, the samples submitted were not suitable for testing, material of this sort ranging from small pieces of shingle to irregularly shaped sections of railroad tie. In a few instances, as when the tide-level testing platform at the Oakland Mole was washed out by a severe storm, with everything attached to it, such samples were unfortunately lost or destroyed before the test could run for an adequate time. This is inevitable in such work, and the Committee's own tests suffered from the same causes.

On account of the limited period of inspection of these tests—a maximum of slightly over 4 years—the Committee is unwilling to give to any of the methods tested its unqualified endorsement. The results, however, as set forth in the following tables, are regarded as affording a useful preliminary indication of the probable success or failure of the treatments used—conclusive for the no small number which failed.

In all of the tables 25 to 27, the letter designations in the first column refer to the several exposure stations, as follows:

A = Oakland Mole.
B = Pier No. 7, San Francisco.
C = Crockett.
D = Mare Island.

Fig. 61. Samples exposed 16½ months at the Oakland Mole. No. A19. Oregon alder considerably attacked by *Limnoria* except in areas where bark remained on. Compare area above the white card with smooth area below, where bark was removed just before photographing. No. A20. Douglas fir sample dipped once in "Elaterite." General attack by *Limnoria* all over surface. No. A21. Douglas fir sample dipped twice in "Elaterite." Heavily attacked by *Limnoria*. Diameter considerably reduced.

TABLE No. 25—RECORD OF PROTECTION TESTS

TESTS OF UNTREATED WOODS FOR WHICH RESISTANCE TO BORER ATTACK IS CLAIMED

Our No.	Submitted by	Description of Samples	Date Submerged	Locality	Date of 1st Attack	Period Exposed	Description of First Attack	Date of Last Inspection	Total Period Exposed	Condition at Last Inspection
A 4	E. A. Howard & Co., San Francisco	Turpentine Wood, untreated	November 1, 1921	Oakland Pier	...	...	...	August 11, 1922	10 months	No attack; sample lost before next inspection.
A15	R. A. Pollock, New York City	Toledo wood (Manbarklak) from Dutch Guiana, 1-ft. sample	January 5, 1923	Oakland Mole	...	...	...	May 27, 1924	17 months	No attack.
B17	R. A. Pollock, New York City	Toledo wood (Manbarklak) from Dutch Guiana, 1-ft. sample	December, 1922	Pier No. 7 San Francisco	...	...	...	November 3, 1925	35 months	Scattered *Limnoria* attack.
C13	R. A. Pollock, New York City	Toledo wood (Manbarklak) from Dutch Guiana, 1-ft. sample	April 25, 1923	Crockett	...	...	...	July 2, 1924	14 months	No attack.
A16	Bethlehem Shipbuilding Corp., San Francisco	Greenheart from British Guiana, 3-ft. sample	January 5, 1923	Oakland Mole	...	...	...	October 10, 1924	21 months	A few *Bankia* in corners, up to 19 mm. long; slight attack by *Limnoria*.
B16	Bethlehem Shipbuilding Corp., San Francisco	Greenheart from British Guiana, 3-ft. sample	December, 1922	Pier No. 7 San Francisco	...	...	...	November 3, 1925	35 months	Scattered *Limnoria* attack.
A17	White Bros., San Francisco	Tallow wood, 3-ft. sample	January 5, 1923	Oakland Mole	...	...	...	May 22, 1924	17 months	Occasional *Limnoria* furrows on surface; no damage as yet.
B 3	White Bros., San Francisco	Tallow wood, 3-ft. sample	January 5, 1923	Pier No. 7 San Francisco	July 19, 1924	18 months	Occasional small *Bankia* up to ¼″ long; no *Limnoria*	November 3, 1925	34 months	Slight attack by *Limnoria* and *Teredo*.
C12	White Bros., San Francisco	Tallow wood, 3-ft. sample	April 25, 1923	Crockett	January 7, 1924	...	Slight *Teredo* attack	July 2, 1924	14 months	A number of small living *Teredo* up to 25 mm. long.
A18	H. Fabre & Cie., Toulon, France	South African Azobe, 4-ft. sample	January 5, 1923	Oakland Mole	...	...	...	May 22, 1924	17 months	No attack.
B15	H. Fabre & Cie., Toulon, France	South African Azobe, 4-ft. sample	December, 1922	Pier No. 7 San Francisco	...	...	...	November 3, 1925	35 months	No attack.
C14	H. Fabre & Cie., Toulon, France	South African Azobe, 4-ft. sample	April 25, 1923	Crockett	...	...	...	July 2, 1924	14 months	No attack.
A19	Frank J. Parker, Kelseyville, Calif.	Oregon Alder, 4-ft. sample	January 5, 1923	Oakland Mole	September 4, 1923	9 months	Scattered *Limnoria* attack where bark was scraped off	May 22, 1924	17 months	Considerably attacked by *Limnoria*, except in a few areas protected by bark (See fig. 61).
B14	Frank J. Parker, Kelseyville, Calif.	Oregon Alder, 4-ft. sample	December, 1922	Pier No. 7 San Francisco	January 10, 1924	13 months	Scattered *Limnoria* attack where bark was scraped off	November 3, 1925	35 months	All gone.
A23 to A27	Southern Pacific Company	Cottonwood, five 5′ lengths	August 18, 1923	Oakland Mole	January 2, 1924	4½ months	Slight attack by *Teredo*	October 10, 1924	14 months	Heavily attacked by both *Limnoria* and *Teredo*.

TABLE No. 26

TESTS OF PATENTED PRESERVATIVES

Our No.	Submitted by	Description of Samples	Date Submerged	Locality	Date of 1st Attack	Period Exposed	Description of First Attack	Date of Last Inspection	Total Period Exposed	Condition at Last Inspection
A 8	Zinsser & Company, New York City.......	Four lengths of Douglas fir, treated with "AcZol"....	January 19, 1922.	Oakland Mole...	April 30, 1923.....	15 months..	Beginning of *Limnoria* attack on all pieces. Bait pieces heavily attacked	May 22, 1924...	28 months..	Rather heavy *Limnoria* attack on all samples, as shown in photo (fig. 62).
A 7	Williams & Francois, Oakland, Calif.........	Two 2-ft. lengths of Douglas fir soaked in Williams and Francois oil............	January 19, 1922..	Oakland Mole...	March 1, 1923 ..	13 months.	Initial *Limnoria* attack on surface of one sample—bait pieces heavily attacked.	May 22, 1924	28 months.	Heavy *Limnoria* attack on one sample, which also showed one large *Bankia* in center when split; initial stages of *Limnoria* attack on other sample. (See fig. 63.)
A20	Cooper-Case-Anderson Company, Filer, Idaho..........	One 3-ft. length of Douglas fir, dipped once in "Elaterite".................	January 5, 1923..	Oakland Mole...	September 4, 1923.	8 months...	Considerable attack by *Limnoria* in areas where paint had flaked off....	May 22, 1924.....	16½ months	General *Limnoria* attack all over surface. (See fig. 61.)
A21	Cooper-Case-Anderson Company, Filer, Idaho..........	One 3-ft. length of Douglas fir, dipped twice in "Elaterite".................	January 5, 1923...	Oakland Mole ..	September 4, 1923.	8 months .	Considerable attack by *Limnoria* in areas where paint had flaked off....	May 22, 1924 .	16½ months	Attacked by *Limnoria* rather more heavily than A20. (See fig. 61.)
B20	Cooper-Case-Anderson Company, Filer, Idaho..........	One 3-ft. length of Douglas fir, dipped once in "Elaterite".................	December, 1922 .	Pier 7 San Francisco...	September 13, 1923	9 months...	Some attack by *Limnoria* especially in areas where paint had been chafed off, but not limited to such areas...........	July 19, 1924 ..	16½ months	Heavy *Limnoria* attack all over.
B21	Cooper-Case-Anderson Company, Filer, Idaho..........	One 3-ft. length of Douglas fir, dipped twice in "Elaterite".................	December, 1922 .	Pier 7 San Francisco...	September 13, 1923	9 months..	Some attack by *Limnoria* especially in areas where paint had been chafed off, but not limited to such areas...........	July 19, 1924	16½ months	Attacked by *Limnoria* more heavily than B20. Diameter much reduced. (In both sets of tests with this preservative, the samples dipped twice were more heavily attacked than those dipped but once.)
A29	J. C. Lynn, San Francisco.........	Four 18" samples of Douglas fir, treated with "Ligni Salvor" as follows: No. 1. Paint coat (single, cold); No. 2. Dipped 5 min. at 180° F. No. 3. Heated to 180° F. and allowed to remain 3 hours, cooling. 4. Immersed at 180° F, heated to 200° F. for 1 hour, allowed to remain in liquid 10 hours, cooling..	September 13, 1923	Oakland Mole...	....	....	....	October 10, 1924..	11 months..	All heavily eroded by *Limnoria*.

TABLE No. 27

TESTS OF SPECIAL CHEMICAL TREATMENTS

Our No.	Submitted by	Description of Samples	Date Submerged	Locality	Date of 1st Attack	Period Exposed	Description of First Attack	Date of Last Inspection	Total Period Exposed	Condition at Last Inspection
A13	Dr. Paul Bartsch* (through Forest Products Laboratory)................	Three 2-ft. pine samples, treated as follows: No. 7 Paraffine, No. 14 Paraffine and copper iodide. No. 24 Paraffine and arsenious iodide................	December 19, 1922	Oakland Mole...	September 4, 1923.	9 months...	Scattered *Limnoria* attack on samples No. 7 and No. 14; no attack on No. 24..............	May 22, 1924.....	17 months..	Heavy *Limnoria* attack on all three samples. (See fig. 64.)
B18	" "	" " "	December, 1922...	Pier No. 7 San Francisco...	September 13, 1923	9 months...	Slight *Limnoria* attack on samples treated with paraffine only, and with paraffine and copper iodide as above. No attack on sample treated with arsenious iodide.	November 3, 1925.	35 months..	Bib all gone; *Limnoria, Bankia* and *Teredo*. (fig. 64.)
C 9	" "	" " "	April 25, 1923.....	Crockett.......	September 6, 1923.	$4\frac{1}{3}$ months.	Minute *Teredo* punctures on all samples.........	July 2, 1924...	$14\frac{1}{3}$ months	Considerable attack of *Teredo* on all samples. Organisms living and of a maximum length of $2\frac{1}{4}$ inches.
A 3	Committee............	Douglas fir treated with 0.06% solution of arsenic and antimony trichloride in petroleum fuel oil.....	October 12, 1921..	Oakland Pier...	....	....	....	August 11, 1922...	10 months..	No attack.
A 10	Arent Laboratories......	Two $2\frac{1}{2}$-ft. lengths of Douglas fir, one treated with creosote antimony trichloride; the other with benzol antimony trichloride.........	January 19, 1922..	Oakland Mole...	March 1, 1923	13 months.	Considerable attack by *Limnoria* on both samples. Bait pieces heavily attacked.............	May 22, 1924.	28 months.	Heavy *Limnoria* attack on both samples; the upper end of each practically destroyed. (See fig. 65.)
A12	Arent Laboratories......	Oak block 6" x 8" x 8", treated with antimony trichloride....................	November 18, 1921	Oakland Mole...	August 11, 1922	9 months..	Slight attack by *Limnoria*	January 2, 1924.	26 months..	Practically destroyed by *Limnoria*. (See fig. 66.)
A14	Forest Products Laboratory..................	Four 18" pine samples treated as follows: No. 1 Barren oil. No. 5, Barren oil with 5% beta naphthol. No. 12 Barren oil, 45%; naphthalene, 55%. No. 15, Barren oil with mercury treatment..................	December 19, 1922	Oakland Mole...	....	....	....	May 22, 1924.....	$17\frac{1}{2}$ months	All showed a few surface furrows of *Limnoria*; No. 12 shows a few spots of somewhat deeper and more extensive attack than the others; but damage as yet is negligible.
B19	" "	" " "	December, 1922...	Pier No. 7 San Francisco...	....	....	....	November 3, 1925.	35 months..	*Bankia* attack; entered only from untreated frame.
C 3	Forest Products Laboratory..............	Four 18" pine samples, treated as follows: No. 1 Barren oil. No. 5, Barren oil with 5% beta naphthol. No. 12 Barren oil, 45%; naphthalene 55%. No. 15 Barren oil with mercury treatment. 3 small round sticks treated as follows: A. Barren oil. B. Barren oil with mercury treatment. C. Barren oil with 55% naphthalene.	November 1, 1922.	Crockett.....	January 7, 1924...	14 months.	A. Attacked by *Teredo*. B and C show shallow surface punctures. The four larger samples intact.............	July 2, 1924..	20 months	A. Entirely destroyed by *Teredo*. B and C show no further penetration than at last inspection.

*Claims treatments not in accordance with best development of his process.

TABLE No. 27.—*Continued*

TESTS OF SPECIAL CHEMICAL TREATMENTS

Our No.	Submitted by	Description of Samples	Date Submerged	Locality	Date of 1st Attack	Period Exposed	Description of First Attack	Date of Last Inspection	Total Period Exposed	Condition at Last Inspection
A28	Standard Oil Co......... (their No. B)	Four 2-ft. samples treated as follows: No. 1. Solution of 10% of organic acids from petroleum naphtha in 90% heavy fuel oil. No. 2. Solution of 5% of organic acids from petroleum naphtha in 95% of heavy fuel oil. No. 3. Solution of 10% of organic acids from petroleum kerosene distillate in 90% of heavy fuel oil. No. 4. Solution of 4½% of copper salts of organic acids from petroleum kerosene distillate in 95½% of heavy fuel oil.......	September 13, 1923	Oakland Mole...	May 22, 1924.....	8 months...	Slight *Limnoria* attack on No. 2...............	November 3, 1925.	26 months..	Nos. 1, 2 and 3 all gone; No. 4, considerable attack by *Bankia*
A28′	Duplicate of A28	" " "	September 13, 1923	Oakland Mole...	....	....	....	November 3, 1925.	26 months..	No attack.
B23	" "	" " "	September 13, 1923	Pier No. 7 San Francisco...	....	....	....	July 19, 1924.....	10 months..	No attack.
B12	Arent Laboratories......	One 2-ft. length of loblolly pine, treated with antimony trichloride........	December, 1922...	Pier No. 7 San Francisco...	September 13, 1923	9 months.	A few *Limnoria* on surface	July 19, 1924.....	16½ months	More heavily attacked by *Limnoria* than untreated controls. (See fig. 67.)
C 8	" "	One 2-ft. length of loblolly pine, treated with antimony trichloride........	May, 1922.......	Crockett.....	....	....		September 6, 1923.	16 months..	No attack.
B4-B7	Barrett Co......... (through Dr. H. Von Schrenk)	Four gates, containing 12 2-ft. samples of loblolly pine, treated with various fractions of coke oven and vertical retort creosotes..	January 6, 1923...	Pier No. 7 San Francisco...	....	....	....	October 11, 1926 .	45 months..	B6 slightly eroded by *Limnoria* on ends; sides intact.
C4-C7	" "	" " "	May, 1922......	Crockett.......	March, 1922	9 months..	Bait pieces attacked by *Teredo*...............	November 2, 1925.	39 months..	C5, C6, C7 in good condition.
B8-B11	" "	" " "	January 6, 1923...	Pier No. 7 San Francisco...	....	....	....	October 11, 1926..	45 months..	Slightly eroded on ends; sides attacked only where specimens were rubbed.

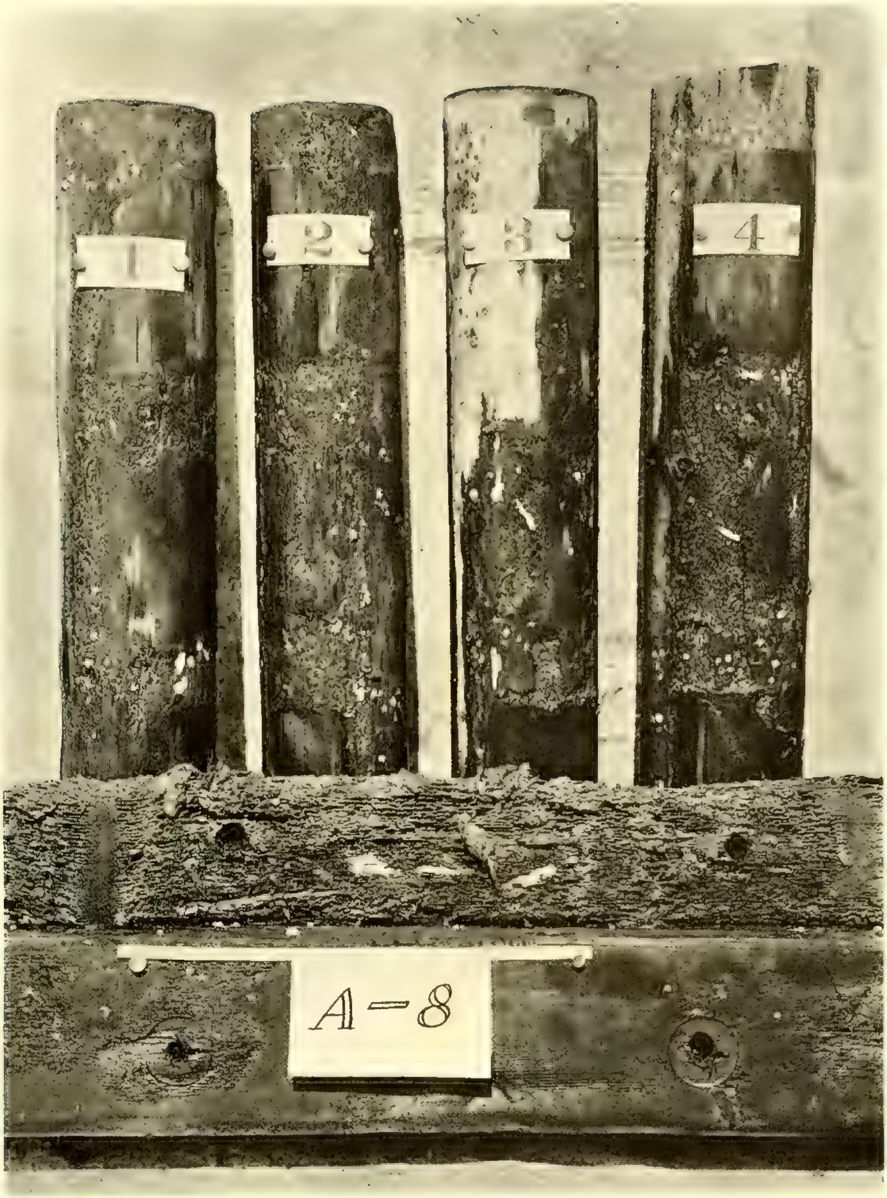


Fig. 62. Test No. A8. Douglas fir samples treated with "AcZol" (Zinsser Co.), photographed after 28 months' exposure. All are considerably attacked by *Limnoria.* Samples 3 and 4 show also the calcareous tubes of *Bankia setacea*, uncovered by *Limnoria* action. At the bottom of the photograph is shown a portion of the creosoted frame in which the samples were held for testing. Just above this is an untreated control, exposed the same length of time, for comparison.

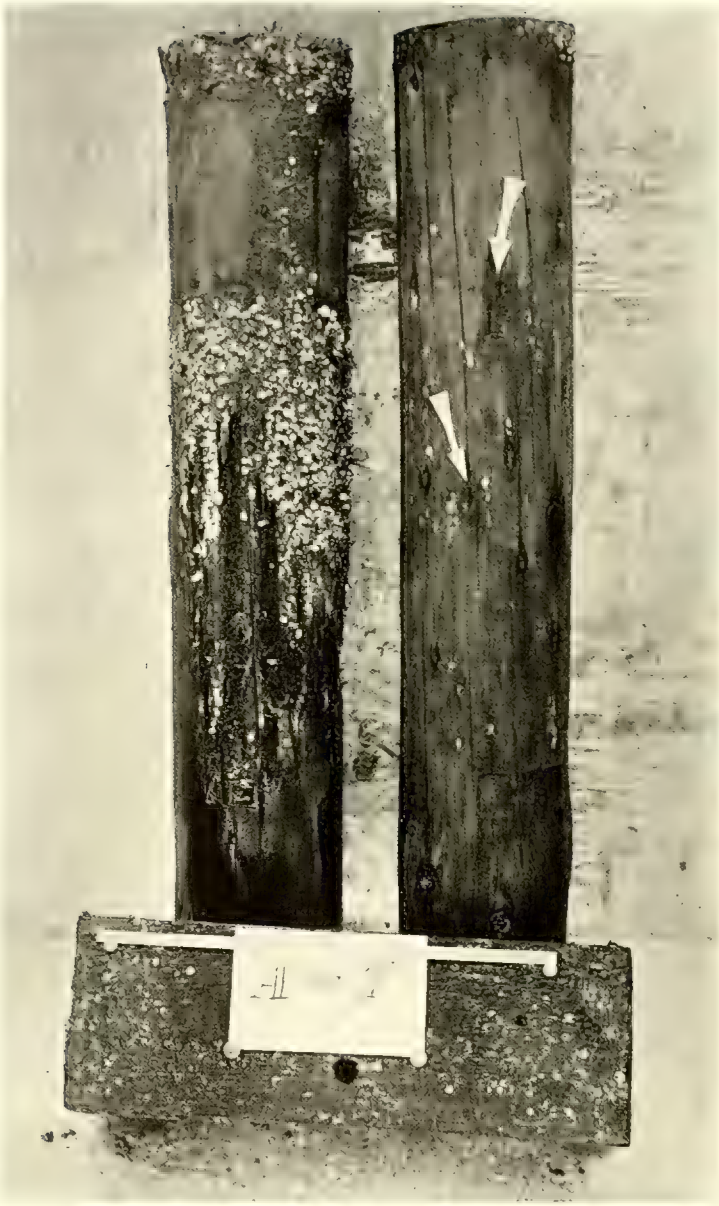


Fig. 63. Test No. A7. Douglas fir samples treated with Williams and Francois oil, photographed after 28 months' exposure. Sample at left shows heavy *Limnoria* attack. Sample at right shows initial *Limnoria* attack, as indicated by arrows. The other depressions in the surface of this sample are knots. Barnacles were scraped from this sample before photographing. Sample at bottom of photograph is a part of the creosoted frame in which the samples were held for testing; it showed no attack, the hole in the center being a bolt hole.

Fig. 64. (1) Test No. A13. Pine samples treated with paraffine after the method of Dr. Paul Bartsch. Photographed after 17 months' exposure. No. 7 is treated with paraffin only, No. 14 with paraffine and copper iodide, and No. 24 with paraffine and arsenious iodide. All heavily attacked by *Limnoria*. Sample at bottom is untreated control.

(2) Test No. B18. Samples No. 8 and No. 15, treated as were No. 7 and No. 14 of test A13. Photographed July 19, 1924, after 31 months' exposure. Attacked by *Limnoria*, *Bankia* and *Teredo*.

Fig. 65. Test No. A10. Douglas fir samples treated by Arent Laboratories with benzol antimony trichloride (No. 2) and creosote antimony trichloride (No. 3), after 28 months' exposure. Both heavily attacked by *Limnoria*. No. 1 is a portion of the creosoted frame, and No. 4 an untreated control.

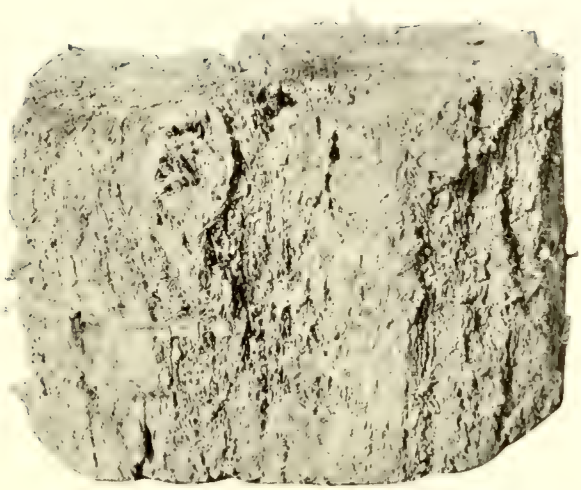


Fig. 66. Test No. A12. Section of oak tie, treated with antimony trichloride by Arent Laboratories, after 25 months' exposure at the Southern Pacific Oakland Mole.

Fig. 67. Test No. B12. Sample of loblolly pine treated with antimony trichloride by Arent Laboratories, (middle), compared with untreated pine and untreated fir on either side; all exposed 16½ months at Pier 7, San Francisco.

BIOLOGICAL SECTION

By Charles A. Kofoid *and* Robert C. Miller
with the collaboration of
Edgar L. Lazier, Walter H. Dore,
Harold F. Blum, *and*
Edgar Van Slyke

CHAPTER XII

BIOLOGICAL ASPECTS OF THE MARINE BORER PROBLEM

The problem of the control of marine wood boring animals is as old as the history of the navigation of the sea. No doubt the first adventurers who undertook the hazards of maritime travel by means of rafts or crude boats inauspiciously learned a lesson in the natural history of these organisms. Certainly they were unpleasantly familiar to the Greeks and Romans, as is indicated by unmistakable references to them in the works of Theophrastus, Cicero, Ovid and Pliny. A lost work of Clitarchus is said to deal with an expedition sent out in the time of Alexander the Great to seek for a teredo-resistant wood.

In man's conquest of the forces of nature, the most powerful enemies with which he has to cope are those which of themselves appear mean and insignificant. The physical obstacles which loomed large in the early history of marine transportation —the dangers of storm and shipwreck, delays due to adverse winds and currents, and the hazards of navigating uncharted seas—have been more and more nearly eliminated. The biological problems involved, however, have not been so successfully coped with. The barnacles and other marine animals which attach themselves in countless millions to the bottoms of ships are quite as much a nuisance now as in days gone by. The shipworm continues to take its toll of wharf piling and wooden boats and barges, even as when Theophrastus (371-286 B. C.) pessimistically observed: "On the land worms destroy the wood, in the sea it is the teredo."

With the rapid increase of shipping in the past two hundred years, the marine borer problem has become more and more a matter of cosmopolitan concern. There are few seaports in the world that are not infested with one or more species of borer, and the facility with which these organisms adapt themselves to new conditions of life has brought about their successful, if unintended, transportation from place to place in connection with shipping, so that in some harbors the damage wrought by indigenous species has been multiplied many times by the importation of more malignant exotic forms. A striking illustration of this is the tremendous damage occasioned by *Teredo navalis* in San Francisco Bay within a few years after its introduction to this locality, damage far in excess of that produced by the native wood-boring mollusk, *Bankia setacea*, which has been known here since the earliest history of the port.

The history of the ravages of marine borers, throughout the world, so far as records are available, has been one of more or less periodically recurring devastations, separated by intervals, often lengthy, of comparative freedom from attack. It is now evident that this apparent cyclical recurrence of heavy borer attack is dependent on combinations of conditions particularly favorable to the growth and multiplication

of the organisms. Just as there are certain years when fruits or grains are exceptionally abundant, so there are years when teredos appear in certain localities in extraordinary numbers. Some of the conditions influencing the varying intensity of attack from year to year will be discussed in a later chapter.

Such recurring attacks of *Teredo* have resulted in a number of spasmodic investigations, stimulated by the immediate necessities of the situation, and left incompleted when the spur to action disappeared through the intervention of natural agencies of control. Only the prospect of sudden calamity, or the unexpected invasion of a new locality has aroused general interest in the matter.

From the time of Pliny until about the sixteenth century the shipworm appears to have fallen quite into oblivion in Europe. Following the discovery of America, it was reported as something new and unusual that in the West Indies ships were seriously damaged by a borer which occurred there. When a little later it was observed that similar organisms were occasioning damage along the coasts of Europe, the earlier accounts of Greek and Latin writers were forgotten and it was generally agreed that the borers had been introduced by ships from foreign lands. Even Linnaeus shared this opinion, and stated in his description of *Teredo navalis* that it had been imported from India.

It seems more probable, however, that the occurrence of the shipworm in Europe had merely escaped general notice during the middle ages, its rediscovery being contingent on circumstances, chief among which was the erection of dykes along the coasts of Holland. The first dykes, which were made by driving piles and heaping up earth behind them, were erected in 1560. Within a few years it was noticed that the piles were being damaged, but apparently there occurred no serious attack until about 1700, when the dykes became damaged to such an extent that inundation of the country was threatened.

The forced practical interest in marine borers which the inhabitants of the Netherlands took at this time occasioned the first serious investigation of these organisms and resulted in a considerable advance in knowledge regarding them. A number of treatises on the natural history of the shipworm appeared during the ensuing half century, foremost among which is the work of Sellius published in 1733, a work of unusual merit for that period and one which retains its place as a classic of the literature on marine borers.

There have been since the time of Sellius some five hundred published references to marine borers, for the most part fragmentary and of little scientific worth, but with a few notable exceptions, which will be referred to farther on. In all this volume of literature, however, there is to be found no single comprehensive account of the biological aspects of the marine borer problem in relation to possible methods of control.

The natural history of the various species of borer is far from being a matter merely of theoretical or academic interest. It cannot be too strongly emphasized that any method of combating the ravages of these organisms must depend for its success on a recognition of the biological factors involved. It has not infrequently occurred in the past that time and money have been invested in proposed methods of protection, the failure of which could have been predicted by the biologist on *a priori* grounds.

From the point of view of the engineer it is of the highest importance to know the various species of borer with which he has to deal, and regarding each, its breeding season, larval habits, distribution, method of attack, the rapidity with which it destroys piling, and the various ecological factors which may alter any of these. In

the light of such knowledge he is in a position to take advantage of the borers, so to speak, and to consistently forestall them in his engineering practice.

For example, in San Francisco Bay the two important species of wood-boring mollusk are *Bankia setacea* and *Teredo navalis*. The former is limited in its distribution to San Francisco Bay proper, while the latter extends its range into the brackish waters of San Pablo and Suisun Bays. The breeding season of *Bankia setacea* is approximately from February to July, that of *Teredo navalis* from July to December, occasionally continuing into January. Now in engineering practice it is often desired to use untreated piling for extremely temporary structures, such as a pipe line to a dredge, or the falsework of some major structure. It could be predicted on the basis of the above facts regarding the distribution and breeding seasons of the borers that untreated piling driven in San Pablo Bay in February would be safe from attack until July. In Suisun Bay the period of immunity would be prolonged by the factor of lowered salinity, and predictions of the probable time of attack could be based on occasional determinations of the salinity of the water.

In the lower bay, on the other hand, no such period of immunity can be expected, as both species of borer occur in this region and their combined breeding seasons occupy nearly the entire year. But as *Teredo navalis* breeds most actively prior to November, and *Bankia setacea* after February, untreated piling driven in the late autumn can be expected to give service for two or three months longer than if driven at other seasons of the year.

Engineers having charge of structures in estuarine waters, where the salinity varies with the tides and at different seasons of the year, can determine, from a knowledge of the minimum salinity requirements of *Teredo*, whether or not it is necessary to take steps to forestall attack by this borer.

Recurring invasions of *Teredo* and the infestation of localities previously immune are not matters of caprice, but depend upon definite combinations of conditions which, properly understood, afford a practicable basis for anticipating attack and adopting intelligent measures of control. It accordingly becomes imperative for the engineer to familiarize himself with the conditions in his own locality, and to know in advance just what problems he may have to meet.

In the program of the investigations of this Committee considerable emphasis has been placed on the biological aspects of the work. Through the continued interest and support of the various cooperating agencies of the Committee and the full cooperation of the University of California, it is now possible to present an extended and comprehensive account of the marine borers of the Pacific Coast, and a detailed analysis of the behavior of these organisms in San Francisco Bay during a four-year period. In preparing the account presented below, the cosmopolitan nature of the marine borer problem has been constantly borne in mind, and an attempt has been made to emphasize those aspects of our findings which are of general rather than merely local interest. It is accordingly believed that this account will be useful to biologists and engineers at large, and it should prove especially valuable to engineers and others who have to cope with the same species or the same conditions encountered here.

ORGANIZATION OF THE BIOLOGICAL WORK

The biological investigations of the Committee have received the services, for longer or shorter periods of time, of six investigators. All have to a certain extent cooperated in all phases of the work, but some mention should be made of the individual contributions which the different workers have made to the progress of the investigation.

The biological work was initiated by Professor Kofoid, and during the early part of the investigation all phases of the work were handled by him, with some student and other assistance. As the scope of the investigations increased, however, it became necessary to enlist other workers, under Professor Kofoid's direction, and to evolve some satisfactory division of labor. Since 1921 the field work and general ecological studies have been the particular province of Dr. Miller. The morphology of *Teredo* was studied in detail by Mr. Lazier during two successive summers. Through the winter and spring of 1922 Mr. Blum made an extensive field and laboratory study of the effect of low salinity on *Teredo navalis.* During the summer of 1922 the aid of Professor Dore was enlisted in a study of the digestion of wood by *Teredo.* From July, 1923, until July, 1924, Mr. Van Slyke was engaged in a special investigation of the biology of *Limnoria.*

Dr. W. D. Ramage, the Committee chemist, has rendered invaluable cooperation in several phases of the biological work.

The original purposes of this Committee, which embraced merely an investigation of the marine borer situation in San Francisco Bay, have been considerably enlarged in consequence of an increasing interest in marine borer problems at other Pacific Coast ports. In 1922 Dr. Miller visited Los Angeles Harbor as a guest of Mr. D. E. Hughes, M. Am. Soc. C. E., and with the assistance of Mr. Hughes and the cooperation of the Los Angeles Harbor Engineer's Office a general reconnaissance was made of the marine borer situation in that harbor. The transfer of Lieut. C. L. McCrae, U. S. N., an active member of this Committee, from Mare Island to San Diego, opened the way for an investigation in San Diego Bay.

In the meantime, the organization of the National Research Council Committee on Marine Piling Investigations and the working out of a suitable plan of cooperation between that committee and the San Francisco Bay Committee resulted in the placing of a series of test boards at various localities on the Pacific Coast, from Alaska to the Gulf of California, and at a few points in the Hawaiian, Samoan and Philippine Islands. Blocks have been removed from these boards at regular intervals and forwarded to the biological staff of this Committee for examination. The test board program has covered a year at each locality.

Thus there has become available a considerable quantity of new data, many of which—indeed most of which—are from localities regarding which little or nothing in this connection was previously known.

Some of the results of the biological investigations which it seemed desirable to make immediately available to those interested have, with the sanction of the Committee, been published in the University of California Publications in Zoology, and elsewhere, as technical papers by the individual investigators. The following papers have thus been published:

Variations in the Shell of *Teredo navalis* in San Francisco Bay, by R. C. Miller. Univ. Calif. Publ. Zool., *22*, 292-328.

Variations in the Pallets of *Teredo navalis* in San Francisco Bay, by R. C. Miller. Univ. Calif. Publ. Zool., *22*, 401-414.

On the Effect of Low Salinity on *Teredo navalis*, by H. F. Blum. Univ. Calif. Publ. Zool., *22*, 349-367.

The Digestion of Wood by *Teredo navalis*, by W. H. Dore and R. C. Miller. Univ. Calif. Publ. Zool., *22*, 383-400.

An Unusual Occurrence of Rock Boring Mollusks in Concrete on the Pacific Coast, by C. A. Kofoid and R. C. Miller. Science, *57*, 383-384.

Morphology of the Digestive Tract of *Teredo navalis*, by E. L. Lazier. Univ. Calif. Publ. Zool., *22*, 455-474.

The Boring Mechanism of *Teredo*, by R. C. Miller. Univ. Calif. Publ. Zool., *26*, 41-80.

Wood-boring Mollusks from the Hawaiian, Samoan and Philippine Islands, by R. C. Miller. Univ. Calif. Publ. Zool., *26*, 145-158.

Wood-boring Crustacea from Hawaii and Samoa, by R. C. Miller. Univ. Calif. Publ. Zool., *26*, 159-164.

Ecological Relations of Marine Wood-boring Organisms in San Francisco Bay, by R. C. Miller. Ecology, *7*, 247-254.

The Salt Error of Cresol Red, by W. D. Ramage and R. C. Miller. Jour. Am. Chem. Soc., *47*, 1230 (1925).

In preparing the present account the freest use has been made of the contents of these earlier papers. Space does not permit, however, a full inclusion of all matters that have been discussed in them. The attempt has been made to set forth in the following pages the more salient results of the biological work, particularly from the standpoint of their bearing on engineering problems. Biologists and others desiring a fuller account of certain items as matters of scientific interest will from time to time be referred to the papers wherein these are discussed in greater detail.

ACKNOWLEDGMENTS

It is difficult, indeed impossible, to acknowledge adequately the assistance given and the courtesies extended to the several members of the biological staff during the progress of this investigation. Hardly a week has passed since the inception of the work in which some signal courtesy has not been offered. Transportation by land and water has been freely made available, labor and often materials have been provided, and routine details of placing and removing test boards and taking water samples have been handled over long periods of time without charge. This assistance has been indispensable to the successful prosecution of the work.

Special mention should be made of a number of organizations which have contributed such assistance in unusual degree. The success of the test board program was due primarily to the cooperation of the U. S. Lighthouse Service. Test boards were installed at the principal Light Stations in San Francisco Bay, and the troublesome routine of installing a new board each month and removing blocks from the old boards was handled with commendable regularity over a period of nearly three years by the lighthouse keepers. Similar cooperation was given at Mare Island and in San Diego Bay by the Public Works Department of the U. S. Navy, and at the latter locality and also in Los Angeles Harbor by the U. S. Army Engineers. Various private corporations have also assisted in the test board program from time to time.

Most of the salinity records have been furnished by the Southern Pacific Company. Water samples were taken at regular intervals at a number of localities by employes of the company, and the salinity determinations were made in the laboratory of the Southern Pacific Creosote Plant at West Oakland. Also, daily salinity and temperature records have been furnished by the California & Hawaiian Sugar Refining Corporation at Crockett and salinities have been taken at frequent intervals at Avon by the Associated Oil Company, and at Martinez by the Shell Company.

Through the courtesy of the Southern Pacific Company a marine laboratory equipped with running fresh and salt water and aquaria for biological work has been maintained for three years on the Southern Pacific Oakland Mole. A similar labora-

tory was provided for a time on the premises of the California & Hawaiian Sugar Refining Corporation at Crockett. These temporary laboratories have been invaluable in the biological investigations.

Full cooperation has been given by the Engineering Department of the Board of State Harbor Commissioners. Numerous courtesies have also been extended by the Los Angeles Harbor Engineer's Office.

The best thanks of the investigators, and of those who may profit by the results, are due to these and other organizations and individuals who have so signally cooperated in the work.

Laboratory space and facilities have been freely made available over a period of nearly four years by the Department of Zoology of the University of California. The laboratories of the Department of Plant Nutrition have been similarly opened for such phases of the work as required biochemical procedure. The investigators wish to express their appreciation of the courtesy of these Departments and further to thank the members of the Advisory Committee appointed by the Regents of the University of California, for their cordial cooperation and assistance.

CHAPTER XIII

THE CLASSIFICATION OF THE SHIPWORMS OF THE PACIFIC COAST AND ISLANDS

The earliest scientific account of the occurrence of marine borers on the Pacific Coast appears to be Tryon's description of *Xylotrya* (now *Bankia*) *setacea* from San Francisco Bay in 1863, in which account it is stated that this species had occasioned considerable damage here several years previously, but "appears since to have become rare." This rarity, however, unfortunately, did not persist, and in the report of the California Board of State Harbor Commissioners for 1871, at which time it was current practice to use untreated piles with the bark on, it is stated that the ravages of the shipworm necessitated the renewal of the piling every three or four years, if not more often. There is in the Museum of the Academy of Natural Sciences, Philadelphia, a specimen of piling taken from San Francisco Bay in May, 1867, which shows the characteristic burrows of *Bankia setacea*. It seems likely that this species is indigenous to the Pacific Coast, its discovery being incident upon the sudden increase of shipping following the gold rush of 1849.

No other species of shipworm was reported from this Coast until 1916, when *Teredo diegensis* was described by Bartsch from San Diego Bay. Shortly afterwards a shipworm was reported by Barrows (1917) from the upper reaches of San Francisco Bay, which was first identified by Bartsch as *T. diegensis*, but later shown by Kofoid (1921) and others to be identical with the well known *Teredo navalis* of European waters. *Teredo diegensis* was, however, found by Kofoid at this time at one locality in San Francisco Bay, namely South San Francisco, thus bringing the number of molluscan borers known to occur in the bay to three.

It is practically certain that *Teredo navalis* has been imported to San Francisco Bay within recent years, probably between 1910 and 1912. The first damage by it was noticed in the Mare Island dykes in January, 1914, although Barrows (1917) considers that an initial infection may have occurred as early as the summer of 1911.

The history of *Teredo diegensis* on this coast is more obscure. This species has been found at one locality in the Hawaiian Islands, and it undoubtedly has occurred in San Diego Bay for a number of years, as Dr. Bartsch states that the specimens on which his description is based were collected by Hemphill, at some time prior to 1896. But whether it was introduced to this coast from the Islands, or to the Islands from this coast, it is not at present possible to say.

The facility with which the shipworms may be carried from place to place and introduced to new localities through the unwitting assistance of oceanic commerce renders the problems of their geographic distribution peculiarly complex; and in most cases the history of any species in this regard cannot be traced with even a remote approach to adequacy.

For the same reason the classification of the Teredinidae is fraught with peculiar difficulties. The adaptability of the shipworms to so wide a range of conditions, and the fact that the same species may be transported from place to place in shipping and so occur in widely separated portions of the world, inevitably results in numerous locality variates. It is difficult, often impossible, to tell whether apparent local races found are generically distinct, or merely represent the immediate impress of the environment on the individual specimens. Furthermore, the shell, which among

other groups of mollusks affords, if not an adequate basis, at least a useful basis for specific distinctions, is in the case of the Teredinidae only occasionally useful for such purposes. This structure, being specialized for boring in wood, is in important features essentially the same in a number of different species, and in minor features the intra-specific variations often cover as wide a range as the inter-specific differences.

The earlier students of these mollusks were more prone to recognize these difficulties than some recent workers. Tryon (1862) stated: "Another difficulty in the study of the Teredinidae is the great variation of the individuals in size, proportions, and markings, making an accurate diagnosis a simple impossibility and compelling us to rely on a *general* accordance with descriptions in the most material points." He further quotes Hanley: "There is one fact with regard to the shipworms, which has rendered their investigation peculiarly laborious, namely, that no reliance can be placed upon the relative proportions of their several parts for specific definition . . . Hence it is absolutely necessary to examine very numerous examples in order to elicit the real and permanent specific characters, and the valves alone are rarely adequate for the determination of the species."

Of possibly greater value for systematic purposes than the shells of Teredinidae are the pallets. These are paired calcareous structures, peculiar to this family of mollusks, which are developed at the posterior or siphonal end for the purpose of closing the orifice of the burrow when occasion arises for so doing. Considerable individual variation also occurs in these structures, and caution must accordingly be exercised in their use as a basis of specific distinctions.

The range of variation occurring in the shells and pallets of *Teredo navalis* in San Francisco Bay and some of the causes which produce such variations have been discussed by Miller (1922 and 1923). This will be referred to in more detail in the later discussion of that species (see p. 432 ff.). The nature and range of such variations in this and other species may be observed from a study of figures 106-109.

It is obvious that if minor variations in the shell and pallets were regarded as having systematic importance, there would be no end to the describing of new species and the already badly tangled taxonomy of the group would be thrown into greater and greater confusion. It is to be hoped that ultimately sufficient data may become available to permit a revision of the classification of the Teredinidae based primarily on anatomical considerations. In the meantime our only refuge from taxonomic chaos is a conservatism in the evaluation of differences in shells and pallets, and a frank disinclination to recognize new species except on the most decided evidence.

Terminology Used in Description

A brief explanation should be introduced at this point of the terms used in description of shells and pallets.

The *shell* is a reduced, sub-globular structure, gaping widely in front for the protrusion of the foot, and behind for the backward extension of the body. It is made up of two *valves* which articulate dorsally and ventrally by specialized knobs. Each valve is made up of three rather distinct lobes, an *anterior*, a *median*, and a *posterior*. The last named portion is frequently referred to as the *auricle*, a term which will be used throughout this discussion in order to simplify so far as possible a confusing terminology arising from the fact that the median lobe of the shell must be further subdivided into three areas, an *anterior median*, a *middle median*, and a *posterior median*. The areas designated by these terms are indicated in figure 68.

The ridges of the anterior lobe are finely serrate, while those of the anterior median are coarsely denticulate; the ridges of these two areas are nearly at right angles to

each other. At the backward margin of the anterior median area the denticles disappear, and the ridges curve sharply and continue across the middle median and posterior median areas and the auricle as ordinary lines of growth.

The interior of the shell (fig. 68) presents several features of interest. The division of the shell into three major lobes is apparent from within as well as from without. The forward edge of the auricle forms usually a prominent shelf by overlapping the posterior median portion. The *apophysis*, a broad flat process extending ventrally from beneath the dorsal articulation of the valves, affords an attachment for certain muscles of the foot.

The *pallets* consist of a pair of calcareous structures, convex on the outer face and flattened or slightly concave on the inner. Attached beneath a fleshy collar at the posterior end of the animal they serve to close the entrance to the burrow when the occupant is in any way disturbed. Each pallet is composed of an expanded portion known as the *blade*, and a narrow cylindrical stalk. In the genus *Teredo* the blade is simple and typically spatulate, while in the genus *Bankia* it is composed of a series of cone-in-cone structures, the pallet having typically the shape and somewhat the appearance of a feather. In a few forms, such as *Bankia excolpa*, this fundamentally compound structure is more or less concealed by an overlying membrane.

In *Teredo* the distal portion of the blade of the pallet nearly always differs somewhat from the basal portion. In such forms as *Teredo navalis* and *T. trulliformis* this difference is limited merely to a greater or lesser darkening of the periostracum of the

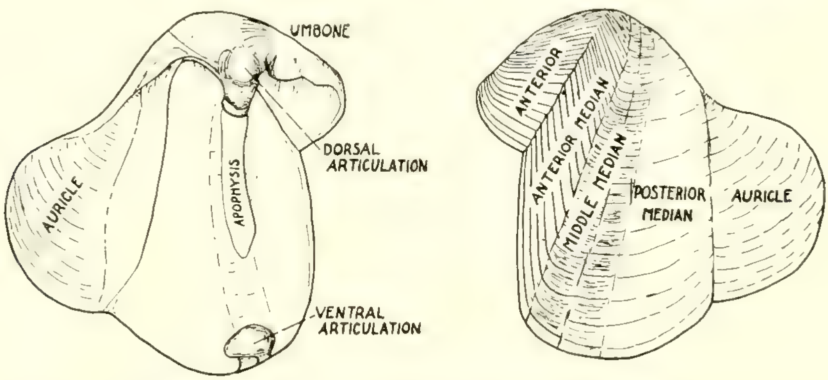


Fig. 68. Interior and exterior views of the shell of *Teredo*, showing terminology used in description.

distal portion of the blade; but in some other forms—*Teredo samoaensis*, T. *diegensis*, *T. affinis*—the blade is made up of two fused but distinctly different elements, which may usually be separated intact.

Key to the Shipworms of the Pacific Coast and Islands

The following key has been prepared with a view to facilitating the identification of the shipworms of the Pacific Coast, and those that are known to occur in the Hawaiian, Samoan and Philippine Islands, although the list cannot be considered complete as regards the latter localities. In these species the characters of the pallets alone are believed to afford a practicable basis for the separation of the different forms, and in the interests of brevity and simplicity shell characters have not been included.

In comparing the relative lengths of blade and stalk, measurements should be taken from the point where the blade begins suddenly to expand or to show marked differentiation from the stalk.

A key of this type is rarely infallible, and reference should be made to the more

detailed descriptions and figures given on subsequent pages in order to confirm identifications made by use of the key.

Throughout the systematic treatment, subgeneric distinctions have been avoided as meticulous.

1. Pallets simple . . . . genus *TEREDO*
    2. Blade of pallets approximately equal to, or longer than, stalk.
        3. Distal portion of blade sharply marked off from basal portion.
            4. Distal portion of blade consisting of a solid capsule . . . . *Teredo samoaensis*
            4′. Distal portion of blade leathery.
                5. Leathery portion of blade investing oval calcareous base as a cap . . . . *Teredo diegensis*
                5′. Leathery portion ending in 2, 3, or 4 irregular finger-like projections . . . . *Teredo affinis*
        3′. Distal portion of blade not sharply marked off from basal portion.
            6. Distal portion of blade slightly narrower than basal portion . . . . *Teredo navalis*
            6′. Distal portion of blade decidedly broader than base.
                7. Stalk ending in an expanded knob . . . . *Teredo mindanensis*
                7′. Stalk club-shaped, not knobbed . . . . *Teredo trulliformis*
    2′. Blade of pallets shorter than stalk.
        8. Blade almost completely invested with a heavy, dark epidermis . . . . *Teredo parksi*
        8′. Blade not invested with a dark epidermis.
            9. Distal half of blade invested with a yellow, horny epidermis . . . . *Teredo bartschi*
            9′. Blade entirely calcified, either perfectly white or with a light yellowish distal portion . . . . *Teredo furcillatus*
1′. Pallets compound, made up of reduplicated elements . . . . . . genus *BANKIA*
    10. Pallets symmetrical, more or less feather-like in appearance.
        11. Margins of separate elements drawn out laterally into slender projections connected by a membrane . . . . *Bankia setacea*
        11′. Margins of separate elements cut off abruptly, without lateral projections or membrane.
            12. Separate elements closely crowded together, their margins much fimbriated both within and without . . . . *Bankia orcutti*
            12′. Separate elements not closely crowded, their margins only slightly fimbriated . . . . *Bankia mexicana*
    10′. Pallets asymmetrical, wholly or partly covered within and without by a periostracum . . . . *Bankia excolpa*

Genus TEREDO

Teredo navalis Linn.

Shell. Anterior lobe of moderate size; auricle variable, typically sub-triangular, but often semi-circular or sub-quadrate, its length being typically about one-half that of the median lobe. The size of the auricle appears to bear an inverse relation to the width of the anterior lobe (cf. figs. 110-111). Color white, often washed with brown, especially from dorsal to ventral across the middle median portion, and sometimes on the auricle.

Pallets. Spatulate, extremely variable in outline, but typically symmetrical, blade urn-shaped, widening regularly from a stalk of medium length, then tapering somewhat toward the tip, which is decidedly excavated. The base of the blade is calcareous, but approximately the distal third is normally covered by a yellowish or brownish chitinous epidermis.

Type. The Linnean type has been lost. The species as at present recognized is typified by the specimen figured by Jeffreys (1865), which is now in the United States National Museum, Cat. No. 194285. Jeffreys' figure is reproduced in figure 69.

Distribution. Europe, from North Cape to the Mediterranean; South Africa; Atlantic Coast of North America; San Francisco Bay; Los Angeles Harbor (occasional).

The wide range of variation in the shell of this species is illustrated in figures 106-109; variations occurring in the pallets are shown in figures 113-114. Some of the causes of this variability will be discussed in detail in a later chapter, together with the question of the specific status of the organism and its general natural history.

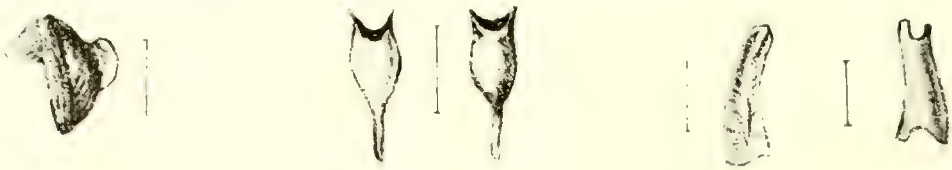


Fig. 69. *Teredo navalis* as figured by Jeffreys (1865).

Teredo parksi Bartsch (1921). Figure 70.

Shell. Grayish white, polished, with ridges numerous and close set; anterior lobe large; auricle consistently small.

Pallets. Stalk long, blade short, broad, deeply excavated at the tip, and covered nearly to the base with a dark brown or black epidermis.

Type. Cat. No. 341132, U. S. National Museum; from Pearl Harbor, Hawaii.

Distribution. Hawaii, Samoa, Philippine Islands.

This appears to be the dominant species in the Pacific Islands. The pallets cannot be confused with those of any other species, and the shell also is more distinctive and less variable than in most others.

Teredo bartschi, Clapp (1923).

Shell. Closely similar to that of *T. navalis*, but with the auricle typically semi-circular rather than sub-triangular in outline.

Pallets. Approaching those of *T. parksi* in form, but having distal half only of blade invested with a periostracum, which is light horn-colored and semi-transparent, permitting the calcareous portion to be seen within as an irregular, hour-glass shaped structure, with a deep sinus on either side.

Type. No. 45301, Museum of Comparative Zoology, Cambridge, Mass.; from Port Tampa, Florida.

Distribution. Atlantic and Gulf coasts, from South Carolina to Texas, with exception of the southern tip of Florida (Clapp); San Diego Bay (rare); Nawiliwili, Hawaiian Islands.

Teredo furcillatus Miller (1924). Figure 71.

Shell. Anterior lobe shorter and narrower than *T. parksi*, and the auricle decidedly longer and broader. The shell is less highly polished and transparent, and the ridges of the anterior median area are more coarsely denticulated than in *T. parksi*.

Pallets. Stem long and blade small, variable in shape, the distal portion deeply excavated on the outer and usually also on the inner face, although the latter in some cases is only slightly notched. The most distinctive feature of the pallets is the absence of a dark periostracum, the distal portion of the blade being either light yellowish or perfectly white. The name is suggested by the resemblance of the pallets to a small two-tined fork (Latin *furcilla*).

Type. No. 1729, Museum of the California Academy of Sciences, San Francisco; from Tutuila, Samoa.

Distribution. Samoa and Hawaii (Honolulu Harbor).

Teredo diegensis Bartsch (1916). Figure 72.

Shell. Similar in outline to that of *T. navalis*, but more finely sculptured and transparent, with numerous close-set ridges. Shell also much smaller than that of *T. navalis* in adult.

Pallets. Blade consisting of an oval calcareous base, surmounted by a horny cap, amber to black in color, depending on age and environment. The horny portion is usually deeply excavated at the tip, but may be cut off bluntly. In dried specimens the extremity of the pallet often forms a sort of blister or knob. The two elements of the blade can usually be readily separated without injury to either.

Type. Cat. No. 74219, United States National Museum; from San Diego Bay.

Distribution. San Diego Bay; Los Angeles Harbor; San Francisco Bay (one locality); Hawaiian Islands.

Teredo townsendi Bartsch (1921) is considered a synonym of *T. diegensis*. A full discussion of this is given in a subsequent chapter.

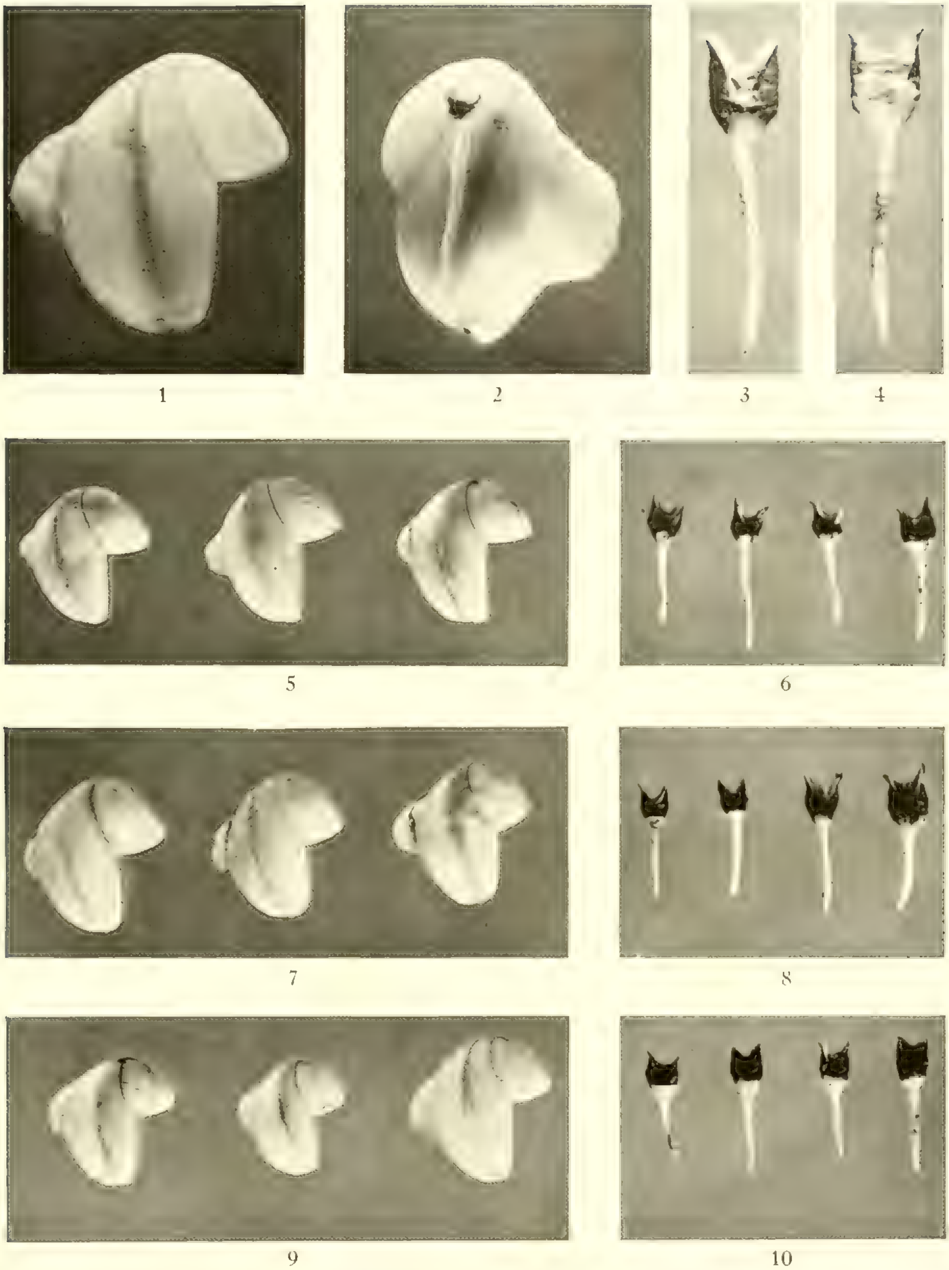


Fig. 70. *Teredo parksi*. *1*. Specimen from Pearl Harbor, exterior of right valve. x 7. *2*. Same, interior of right valve. *3*. Same, outer face of pallet. *4*. Same, inner face of pallet. *5*. Shells of *T. parksi* from Cavite. x 5. *6*. Pallets of *T. parksi* from Cavite. x 5. *7*. Shells of *T. parksi* from Honolulu Harbor. x 5. *8*. Pallets of *T. parksi* from Honolulu Harbor. x 5. *9*. Shells of *T. parksi* from Tutuila. x 5. *10*. Pallets of *T. parksi* from Tutuila. x 5.

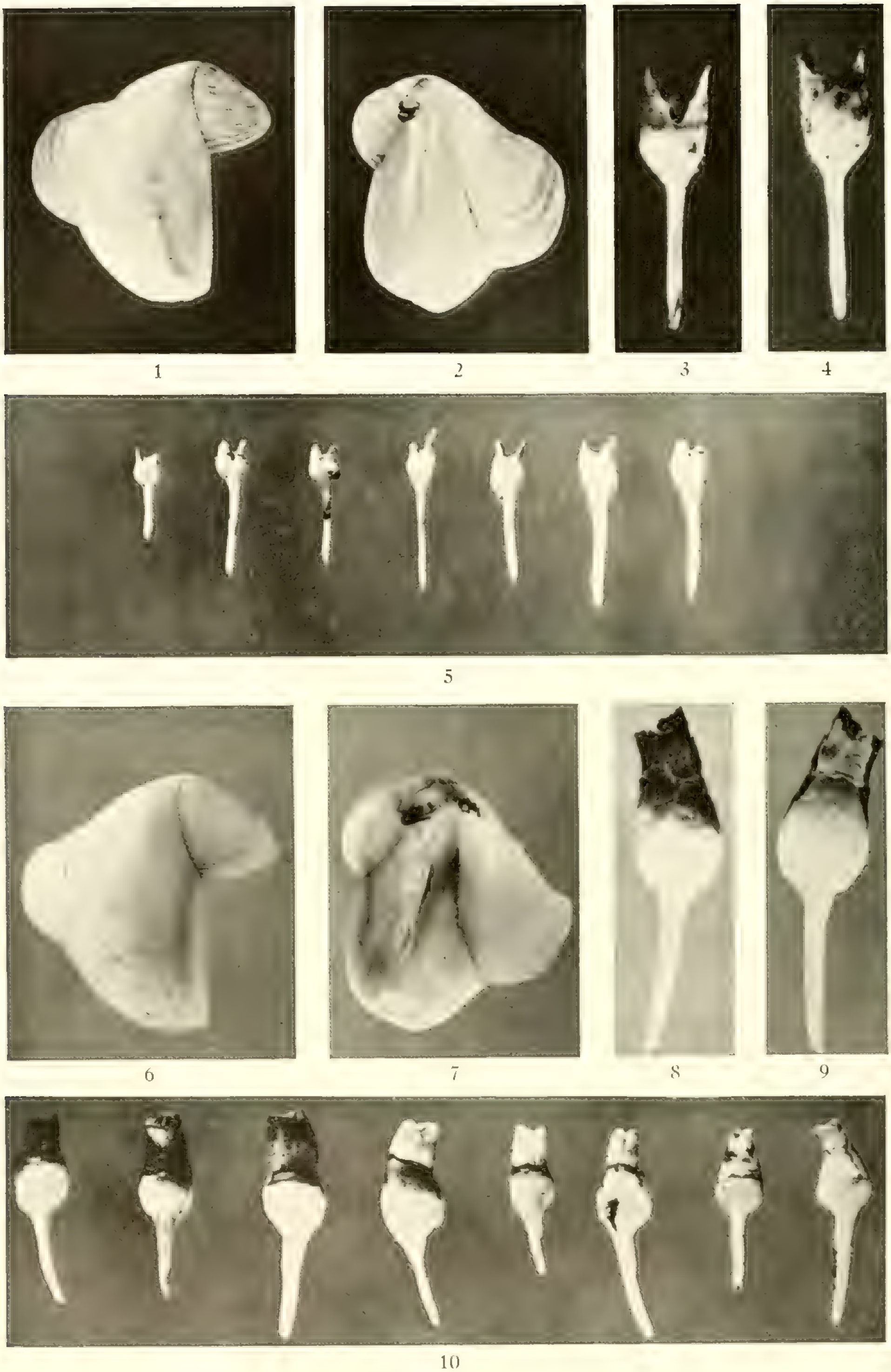


Fig. 71. *Teredo furcillatus*. *1*. Exterior of right valve of the type. x 10. *2*. Same, interior of right valve. *3*. Same, inner face of pallet. *4*. Same, outer face of pallet. *5*. Series of pallets selected to show variations. x 7. *6*. *Teredo samoaensis*, exterior of right valve of the type. *7*. Same, interior of right valve. *8*. Same, outer face of pallet. *9*. Same, inner face of pallet. *10*. Series of pallets selected to show variations. x 7.

Teredo affinis Deshayes (1863). Figure 73.

Shell. Similar to that of *T. furcillatus*, but with the anterior lobe in general narrower and the auricle broader, differences which have been fairly constant in all the specimens examined.

Pallets. Stalk long and slender; blade consisting of a short, urn-shaped calcareous base, surmounted by a dark brown, chitinous distal portion, wholly uncalcified, and of very irregular shape. In specimens considered typical the distal portion consists of a narrow, elongate, cupped median extension, very deeply excavated on the outer, less deeply on the inner face; and further cut away on each side nearly to its juncture with the calcareous base, where the chitinous portion is spread out abruptly and slightly excavated to form two shallow lateral cups. As a result of wear the median extension may be excavated

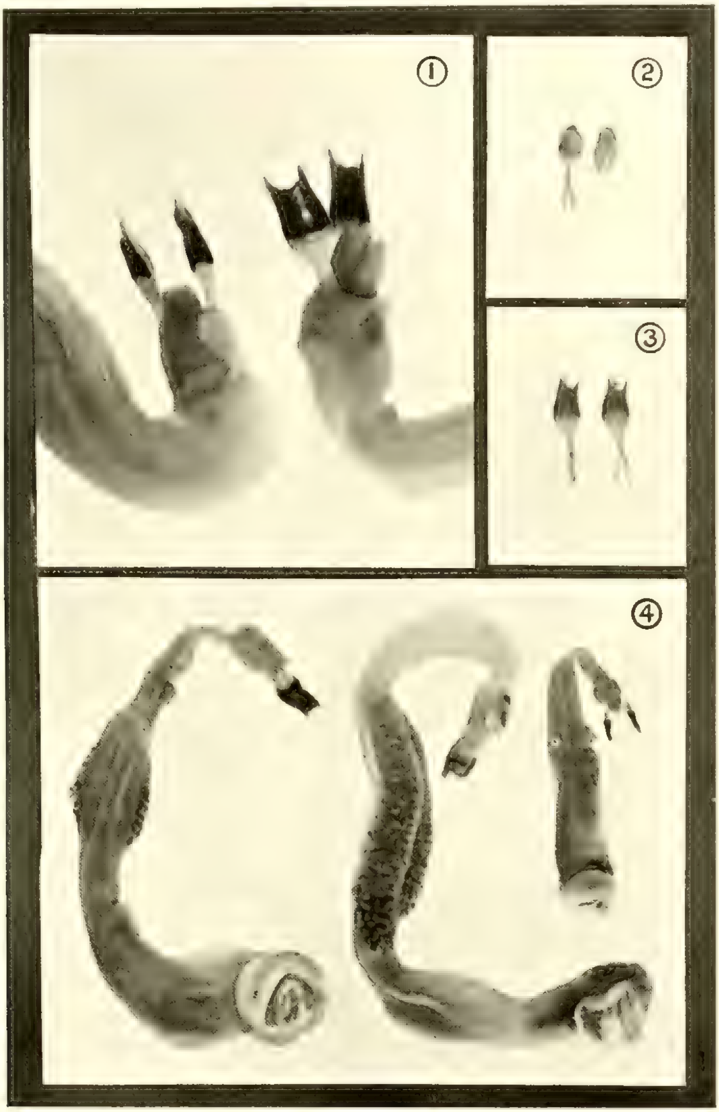


Fig. 72. *Teredo diegensis.* *1.* Posterior ends, showing pallets and siphons. *2.* Pallets with corneous tips removed. *3.* Normal pallets. *4.* Entire animals, showing enlarged brood sac, with enclosed larvae. All figures larger than natural size.

nearly to the base, within as well as without, so that the pallet appears to end in two slender leathery fingers. The lateral excavations are usually unequal, and one or both may be entirely lacking. The calcareous base is cut off abruptly at its juncture with the distal chitinous portion.

Notwithstanding the irregularity in the form of the pallets, the characteristic leathery distal pro-

jections enable them to be recognized almost at a glance. But the chitinous portion rather readily comes free of the calcareous base, which then has a deceptive appearance of completeness and might be mistaken for a pallet of some other species.

Type. This species was described by Deshayes (1863) from Reunion Isle. The type apparently has been lost. Dr. E. Lamy informs us that it is not in the Paris Museum.

Distribution. Reunion Isle; Hawaiian Islands (Nawiliwili and Honolulu Harbor).

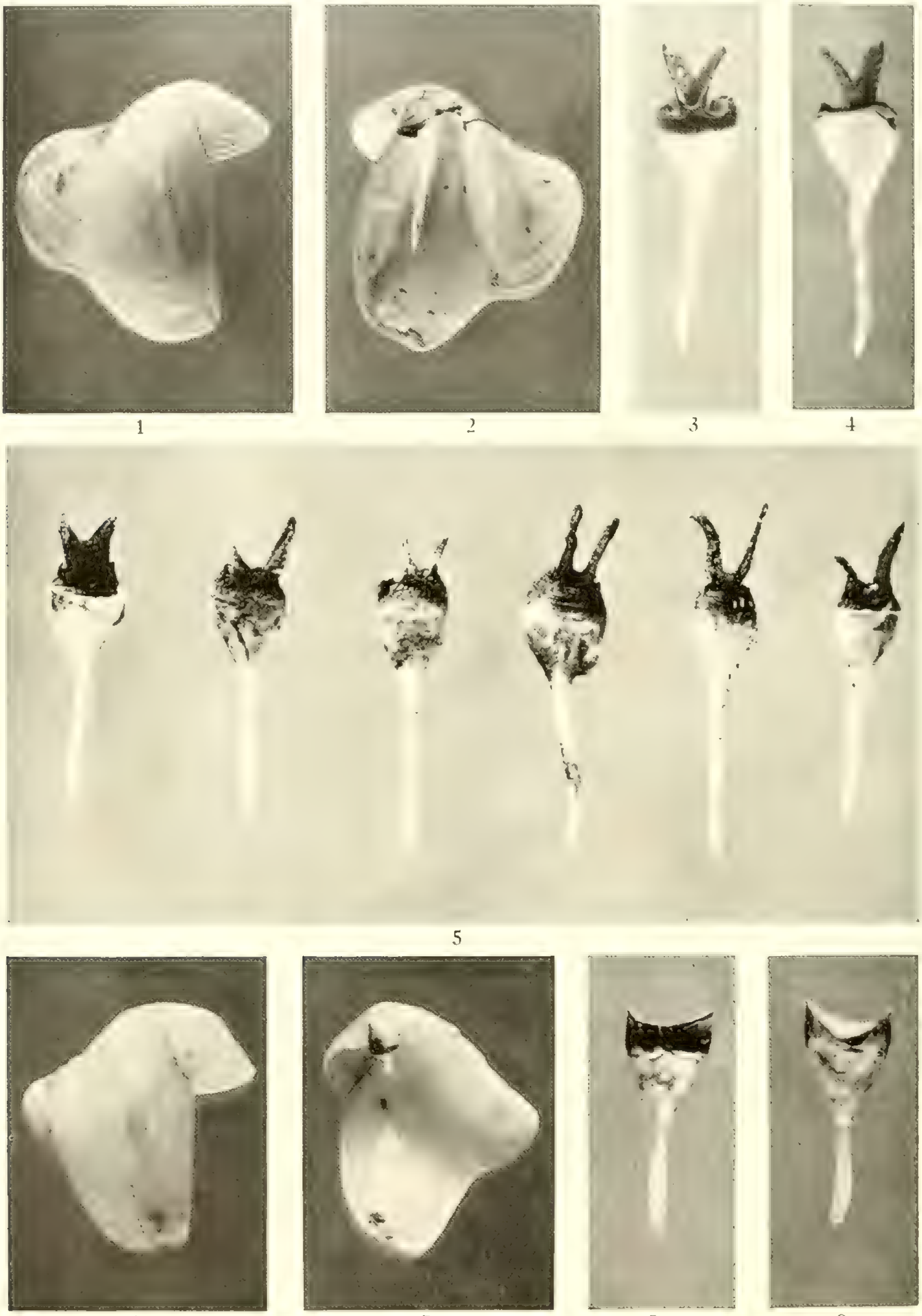


Fig. 73. *1* and *2*. *Teredo affinis*, exterior and interior views of right valve. *3* and *4*. Pallet of same, outer and inner face. *5*. Series of pallets selected to show variations. *6*, *7*, *8* and *9*. *Teredo trulliformis*, type. All photos x 10.

Teredo samoaensis Miller (1924). Figure 71.

Shell. Similar to that of *T. furcillatus*, but generally more transparent and with a smaller auricle. Interiorly the shell is characterized by a very broad, irregular apophysis, which is a useful, although not infallible guide in the identification of the shell.

Pallets. Stalk of medium length; long tapering blade, which is divided into two distinct portions. The basal portion, comprising about one-half the length of the blade, is broadly ovate and calcareous; the distal portion is narrower, nearly straight-sided, forming a more or less completely calcified semi-

Fig. 74. *Bankia setacea*, entire animals. × ¾.

cylinder, flattened on the inner face, slightly cupped at the extremity. At the juncture of these two elements the pallet is encircled by a band of brown epidermis, which sometimes more or less completely envelops the distal portion.

Type. No. 1730, Museum of the California Academy of Sciences, San Francisco; from Tutuila, Samoa.

Distribution. Thus far found only in Samoa.

Teredo trulliformis Miller (1924). Figure 73.

Shell. Auricle much reduced, and so fused with the posterior median portion that the boundary between the two can scarcely be detected on the exterior surface. Interiorly the auricle overlaps the posterior median portion a little distance, and its anterior edge can be distinguished, but does not form a shelf with a cavity behind it as it does in all of the foregoing species.

Pallets. With short, broad blade; stalk of medium length, which, instead of tapering gradually toward the end, becomes slightly expanded, like the handle of a trowel (Latin *trulla*). The distal portion of the blade is covered by a grayish or brownish epidermis, and the extremity is characterized by a shallow crescent shaped excavation.

Fig. 75. Pallets and siphons of *Bankia setacea*. Magnified slightly.

The posterior end of the tube is divided by a calcareous partition, forming two siphonal openings. The blades of the pallets are at right angles to this partition.

Type. No. 1731, Museum of the California Academy of Sciences, San Francisco; from Honolulu Harbor.

Distribution. Thus far known from Hawaiian Islands only.

Teredo mindanensis Bartsch (1923).

Shell. Small, transparent, white; regular in outline, similar to *T. navalis;* characterized by numerous fine, close-set ridges.

Pallets. Blade nearly triangular, with apex at insertion of stalk; distal portion not different from base. The stalk expands suddenly at its free end into a distinct knob, which is the most striking characteristic of this species.

Type. Cat. No. 310975, United States National Museum; from Mindanao, Philippine Islands.

Distribution. Thus far known only from the type locality.

Genus BANKIA

Bankia setacea Tryon (1863). Figures 74 and 75.

Shell. Anterior lobe relatively small; auricle of medium size, its posterior margin semi-circular in outline. Ridges numerous and close-set. Anterior median area nearly always suffused with brown, especially dorsally. Adult shells typically much larger than any of the foregoing.

Pallets. Decidedly feather-like in appearance, the blade consisting of a series of cone-in-cone elements which are drawn out laterally into slender projections, with a thin membrane stretched between.

Type. Museum of the Academy of Natural Sciences, Philadelphia; from San Francisco Bay.

Distribution. Pacific Coast, from Kodiak Island to San Diego Bay.

Bankia mexicana Bartsch (1922).

Shell. Closely similar to that of *B. setacea.*

Pallets. Blade consisting of a series of cone-in-cone elements, the distal margins of which are cut off abruptly, without the lateral prolongations and the connecting membrane.

Type. Cat. No. 194176a, United States National Museum; from Sinaloa, Mexico.

Distribution. West Coast of Mexico.

Bankia orcutti Bartsch (1923).

Shell. Small, with a broad posterior median portion and an auricle of moderate size.

Pallets. Made up of closely crowded elements, the free margins of which are much fimbriated, so that each segment has a comb-like appearance.

Type. Cat. No. 348191, United States National Museum; from Bacochibampo Bay, Sonora, Mexico.

Bankia excolpa Bartsch (1922).

Shell. Small, with a narrow median lobe and reduced auricle.

Pallets. Asymmetrical, the stalk being inserted to one side of the median line; the blade made up of closely apposed elements wholly or partly covered on both the inner and outer faces by a periostracum.

Type. Cat. No. 98763, United States National Museum; from the Gulf of California.

The foregoing descriptions are based on specimens taken during the present investigation, with the exception of the descriptions of *Teredo mindanensis*, *Bankia orcutti* and *Bankia excolpa*, of which no specimens have come to hand. The types of these three species have been examined by Dr. Miller, however, who finds no reason to question their validity. Brief descriptions of them have therefore been included, in order that the present report may be as complete as possible.

THE QUESTION REGARDING THE OCCURRENCE OF TEREDO NAVALIS IN SAN FRANCISCO BAY

Some question has arisen as to whether or not the species of *Teredo* responsible for the recent damage in the upper portions of San Francisco Bay is actually identical with the *Teredo navalis* of European waters. This matter is of itself of little import, and would not merit extensive discussion except for the fact that certain rather weighty practical considerations are involved. If the species of *Teredo* with which we are working be not the *Teredo navalis* of Europe, then our problem in San Francisco Bay is more or less detached, and of only passing interest elsewhere. If, however, the organism which has appeared in recent years in San Francisco Bay is indeed the well known pest of the Old World, a number of important considerations are immediately evident.

The first of these considerations is that *Teredo navalis* is an organism of potentially cosmopolitan distribution, at least within the confines of the temperate zones. It is capable of being carried from place to place in the path of commerce, of establishing itself in new localities, and repeating its history of depredations in regions where it has been previously unknown.

A second and equally important consideration is that, if the organism with which we are dealing be the true *Teredo navalis*, our findings in connection with it will be applicable elsewhere, wherever this species is now distributed or may in future appear. Hence, on the intrinsically unimportant problem of the identity of this organism hinges the question as to whether the present investigation is of merely local, or of cosmopolitan, interest.

The organism found by Barrows (1917) in the Mare Island dykes in 1914 and subsequently, was identified by Bartsch as *Teredo diegensis*. It was later identified by Kofoid (1921) as *Teredo navalis*. Bartsch (1922) thereupon rescinded his original identification, and stated that the organism in question was *Teredo townsendi* (a synonym of *Teredo diegensis;* see p. 198). This, however, is undoubtedly erroneous, as *Teredo diegensis* (= *townsendi*) occurs at only one locality in San Francisco Bay—South San Francisco—and there is no evidence of its ever having penetrated into San Pablo Bay.

Bartsch (1921) had in the meantime described certain specimens from San Pablo Bay as a new species, *Teredo beachi*. It was reaffirmed by Kofoid and Miller (1922) that the organism occurring in San Pablo Bay was identical with the well known *Teredo navalis* of European waters, and it was shown by Miller (1922 and 1923) that the characters by which *T. beachi* was presumed to be differentiated from *T. navalis* were matters of individual or environmental variation, and not of specific rank.

The authors are convinced that the organism in question is true *Teredo navalis* on the ground of its close resemblance to that species as occurring in European waters, and from the following additional considerations:

The hardy nature of the organism and its ability to survive for long periods under adverse conditions indicate that it may readily be carried from place to place in connection with shipping, and succeed in establishing itself in new localities. Our experiments have shown that it will live indefinitely in salinities of from 5 parts per 1000 to 60 parts per 1000 (nearly twice that of normal sea water), and that it will survive for long periods of time in an almost complete absence of oxygen. In short, it has withstood in the laboratory conditions of stress to which it would rarely or never be exposed in nature. The evolution of the organism has been in a direction to enable it to take advantage of submerged timber wherever found. It has become adjusted to this one major factor rather than to salinity, temperature, depth, or similar factors

which play so important a role in the economy of most marine organisms. Hence the usually recognized zoogeographic factors are of relatively minor importance in limiting the distribution of this species.

This point is borne out by the fact that *Limnoria lignorum*, an organism belonging to an entirely different group, but likewise specialized for boring in wood, has a remarkably cosmopolitan distribution.

The sudden and catastrophic activity of this particular *Teredo* in San Francisco Bay would appear to be proof positive that it has been introduced from some other locality. The Pacific Coast has been ransacked for decades by conchologists, but this organism has never been found until recent years. Its behavior since its discovery in San Francisco Bay in 1914 is of such a nature that it is highly improbable that it could have been present in earlier years and escaped notice. Untreated piling at Port Costa driven prior to 1870, so far as can be determined was untouched by *Teredo* prior to the recent outbreak, although several periods of low rainfall had intervened which would have been favorable to such an outbreak had the organisms been present.

Our specimens from San Francisco Bay compare closely with specimens of *T. navalis* which we have received from various localities in Europe and along the Atlantic Coast of North America. A detailed study of a large series of shells and pallets (Miller, 1922 and 1923) has brought out the fact that the range of the variations produced by different conditions in different portions of the Bay, and even by the different conditions obtaining at the top and bottom of the same pile, is of greater magnitude than the differences that have been stated to exist between the type of *T. navalis* and the San Francisco Bay form. Specimens from San Francisco Bay which we have sent to Paris have been identified by Dr. E. Lamy of the Museum d'Histoire Naturelle as *T. navalis*, and Dr. W. T. Calman of the British Museum writes that our figures are undoubtedly of that species.

It appears therefore that there are sound biological reasons for believing that the species we have under consideration is true *Teredo navalis*, which has lately been introduced here from some other area of distribution.

CHAPTER XIV

MORPHOLOGY OF THE SHIPWORM

The anatomical structure of the shipworms is extremely interesting, both from the point of view of the coordination of structure and function, and from that of comparison with related types which live under less unusual conditions. On superficial examination, *Teredo* would appear to bear hardly a remote resemblance to such a form as the common soft shell clam, *Mya*. But on dissection it is found that the organ systems and their relations in the two forms are essentially the same, and the families Myidae and Teredinidae are placed in adjoining sub-orders in modern systems of classification.

As compared with *Mya*, the body of *Teredo* is greatly elongated, the visceral mass occupying approximately the anterior fourth of its length, and the gills the remainder. The small, nearly globular, bivalve shell is much reduced, so that it covers only a small portion of the anterior part of the body. In comparison with less specialized lamellibranchs, and indeed from a consideration of its own early development, *Teredo* may be regarded as having greatly outgrown its shell posteriorly. Most of the organs therefore lie back of the posterior adductor muscle, instead of anterior to it as in other bivalves.

Although thus out of their normal positions, the organ systems nevertheless maintain in considerable degree their original *relations*. The kidneys, heart and pericardium have been elongated and rotated about the posterior adductor muscle through an arc of 180 degrees, so that their morphologically posterior end becomes anterior, and their dorsal side ventral. This places the kidneys above the pericardium, and the renal orifices at the posterior end of the viscera. The genital orifices have followed the renal orifices posteriorly, but the gonads cannot be regarded as having taken part in the rotation about the posterior adductor, as they still maintain a position ventral to the pericardium. The visceral ganglion has moved from its position beneath the posterior adductor muscle to the posterior tip of the visceral mass. The cerebral and pedal ganglia and their connectives form the usual ring about the oesophagus.

The mouth and anus retain their usual positions, the former between the anterior adductor muscle and the foot, and the latter on the dorsal side of the posterior adductor. The oesophagus is the typical short, flat ciliated tube. The stomach, however, is greatly elongated and relatively large. Its capacity is further augmented by a long, cylindrical caecum opening from its posterior end. The usual crystalline style and its mechanism are well developed, the sac of the style lying in the small, discoidal foot of the animal. The digestive glands are large and are closely applied to the stomach. The intestine, which in *Mya* is coiled upon itself, may be regarded in *Teredo* as having been uncoiled and extended posteriorly in a long loop about the caecum. It does not pass through the heart, as in Mya, nor through the pericardium. The anus opens into a long anterior diverticulum of the suprabranchial cavity, the anal canal. More detailed comparisons with the typical lamellibranch structure will be made as the various systems are considered.

The following account is based primarily on the anatomy of *Teredo navalis*, with occasional reference to what is known of other species of shipworm.

Anteriorly the gills become separated by the visceral mass, and each continues forward as a mere rudiment to the region of the mouth. Here each again spreads out

into a few filaments, forming the anterior gills (fig. 76, *a.g.*) just back of the labial palps.

The free ventral edge of each gill is characterized by a longitudinal groove, the branchial groove (fig. 76, *b.g.*), which extends uninterruptedly from the posterior to the anterior extremity of the gills. This groove is lined with cells which bear cilia, the function of which is to sweep food particles forward to the region of the mouth.

The structure which connects the anterior gill with the posterior gill on each side consists merely of a rudiment suspended from the roof of the infrabranchial cavity, which bears along its ventral margin the branchial groove. This rudiment of the gill is not divided into transverse filaments, but itself represents morphologically a single greatly broadened filament (Sigerfoos, 1908).

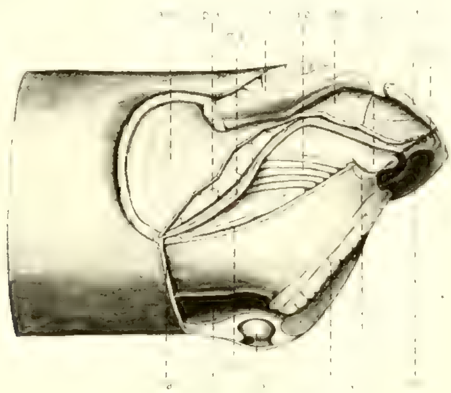


Fig. 76. *Teredo navalis*, external view of the anterior end of the body from the right. x 7. Part of the right valve and mantle have been dissected away. *a.a.* Anterior adductor muscle. *a.f.* Anterior pallial fold. *a.g.* Anterior gills. *au.s.* Auricle of the shell. *b.g.* Branchial groove. *d.f.* Dorsal pallial fold. *d.l.p.* Dorsal labial palp. *f.* Foot. *ib. c.* Infrabranchial cavity. *m.* Mouth. *ma.* Mantle. *p.a.* Posterior adductor muscle. *sh.* Shell. *v.a.* Ventral articulation of the shell. *v.l.p.* Ventral labial palp.

When *Teredo* is undisturbed, the respiratory process is carried on continuously. A stream of water, drawn in through the incurrent siphon, passes forward in the infrabranchial cavity, over the gills and through the gills, between the transverse filaments, into the suprabranchial cavity, whence it passes again to the outside of the body through the excurrent siphon. Thus there is normally a continual movement of water forward in the infrabranchial and backward in the suprabranchial cavity, while through each slit between the transverse filaments a small portion of the moving water passes from the incoming to the outgoing stream. The interior of each lamina of the gills is occupied by blood spaces, and as the water passes between the laminae, oxygen is absorbed from the water and carbon dioxide is given off.

The oxygen requirements of lamellibranchs are extremely low, and it is probable that the respiratory process can be suspended for an indefinite period of time without serious inconvenience when the animal is disturbed, or is forced by unfavorable conditions to retract its siphons and close the burrow with the pallets. In such instances the water retained in the burrow affords a supply of oxygen for a time, and the oxygen requirement of the occupant is still further reduced by the cessation of most of its normal activities. Even so, the teredo will often survive in a closed burrow long after the oxygen supply of the water in the burrow is presumably exhausted.

THE MECHANISM OF FEEDING

As will later be shown, a considerable portion of the nourishment of *Teredo* is derived from the wood in which it bores. But a part of its food is undoubtedly made up of plankton organisms, which are being continually taken in with the respiratory current.

A somewhat detailed account of the ciliary mechanism for the capture and transportation of food in *Mya*, the soft-shelled clam, has been given by Yonge (1923). No such investigation has been made in the case of *Teredo*, but a few preliminary observations indicate that a similar apparatus is present. Foreign particles touching any part of the body wall, mantle, or gills are immediately entangled in mucus secreted by the epithelium. Anything falling on the gills is quickly carried by cilia to the nearest branchial groove, the cilia of which bear material rapidly forward to the region of the mouth.

The dorsal and ventral lips of the mouth are continuous, respectively, with a pair of dorsal and a pair of ventral labial palps. The dorsal palps in *Teredo* navalis are small and inconspicuous, but quite distinct (fig. 76), while the ventral ones are reduced to slightly raised, ciliated patches on the sides of the foot. The under sides of the dorsal palps are also ciliated. The labial palps of other lamellibranchs are a part of the mechanism for bringing plankton food to the mouth, and this function is doubtless retained in Teredo.

In *Bankia setacea* the labial palps, both dorsal and ventral, are rather well developed. Deshayes (1848) and Quatrefages (1849) figured two pairs of long, narrow palps in species studied by them. It appears evident that these structures will, in some cases at least, be of value in systematic distinctions.

Teredo is unlike the more generalized lamellibranchs in that cilia do not cover the visceral sac and the interior of the mantle, but are restricted to a narrow strip on the mantle opposite the branchial groove. These cilia beat in such a way that particles entangled in mucus are borne rapidly toward the posterior end of the infrabranchial cavity. If the branchial groove is carrying forward more than a very small amount of material, it is, without doubt, caught away and carried back by these cilia. Thus we have a mechanism which determines, on the basis of quantity, not of quality, whether or not matter taken from the water shall reach the mouth.

Particles falling on the non-ciliated surface of the mantle or body are drawn into a ciliary current by the strands of mucus that are secreted. Material that is carried posteriorly by the cilia on the mantle collects in the posterior part of the infrabranchial cavity, and is expelled at intervals through the incurrent siphon, apparently by a quick contraction of the mantle. This corresponds to the action of other mollusks with a closed mantle as described by Kellogg (1915), except that there the adductor muscles effect the contraction. The details of the ciliary mechanism of *Teredo* remain to be worked out, but it is apparent that there exists an apparatus similar to that of other lamellibranchs for the capture and transportation of plankton.

THE DIGESTIVE TRACT

The *mouth* of *Teredo*, as in most bivalves, is a small, median, transverse slit, dorsal to the foot. The *oesophagus* is short, dorso-ventrally compressed, and heavily ciliated throughout its length. It narrows posteriorly, so that its width at the stomach is about one-half that at the mouth. In the walls are several longitudinal furrows.

The stomach (figs. 77 and 78) is long and subcylindrical. Most of the digestive glands lie on the right side of the visceral mass, so that the stomach lies somewhat to

the left. Its anterior end is broadened toward the right, and the posterior end is somewhat dilated.

The stomach is always found nearly empty of food. Serial sections show a great deal of coagulated, lightly staining digestive juices, with a small amount of wood fibers and plankton. This can be seen in figure 79. The other parts of the alimentary canal are usually full of wood chips or mingled wood chips and plankton, indicating that the passage of food through the stomach is relatively rapid.

The *digestive glands* or *livers*, which primitively are paired evaginations of the walls of the stomach, are broken up into a number of glandular masses in *Teredo*, each emptying into the stomach by one or more orifices. The glands are closely applied to the walls of the stomach, so that no exposed ducts are present. Food material enters the lumina of at least some of the ducts. For convenience we have designated anterior, ventral, and posterior livers. None of these except the posterior one is a single mass.

In the pedal region there is a considerable amount of digestive gland, the anterior liver (*a.l.*, figs. 77 and 78). This communicates with the stomach by several orifices of varying sizes in the right wall, and by one in the left wall. The latter orifice is in the anterior wall of the lateral pouch (*l.p.*, fig. 78).

The ventral livers (*v.l.*, figs. 77 and 78) are small, and communicate with the stomach by four small orifices (*v.l.o.*, fig. 77).

The *posterior liver* (*p.l.*, figs. 77, etc.) is a large gland lying on the right side of the stomach at its posterior end. Its large duct opens to the stomach by a very large circular orifice. Deshayes (1848) describes many hepatic orifices in this region, instead of the single large one found here and in Sigerfoos' (1908) species.

Although the posterior liver is externally a unit, it is divided into two parts differing histologically. The cells composing the dorsal part are columnar, making the walls of the acini thick, while the cells of the ventral part are hardly higher than the diameter of their nuclei. This differentiation is indicated diagrammatically in fig. 77, and the external appearance is shown in fig. 78, 3. The difference in the appearance of the tissues is quite marked in the photomicrographs, fig. 79, 1-3. Sigerfoos (1908) and Potts (1923) describe this same condition. The anterior and ventral livers present no such differentiation.

Besides the livers, the stomach bears four other diverticula: the caecum, the sac of the crystalline style, the dorsal caecum, and the lateral pouch. The most conspicuous is the large posterior *caecum*. This equals or exceeds the stomach in capacity. It is cylindrical in shape, but the ventral wall is infolded to form an elaborate, two-coiled typhlosole (*c.t.*) extending its entire length. This caecum is always found full of wood chips, and it is here presumably that digestion and absorption of wood principally takes place (see, however, p. 243). Only rarely have evidences of plankton been found in it, although they are common in the intestine. The great capacity of the caecum allows the wood, which is probably slow to digest, to remain there for some time. The typhlosole has a large area for absorption, and has an adequate blood supply. A large artery carries aerated blood directly from the heart to the anterior end of the caecal typhlosole. The term *caecal artery* seems appropriate for this vessel (*c.a.*, figs. 77 and 79). After passing through the typhlosole the blood bearing assimilated food flows into the sinuses in that part of the body.

Sigerfoos (1908) states that the interior of the caecum in the species he studied is ciliated. None of the present writers' preparations show any cilia whatever in the caecum, nor are the cells of the tall columnar variety which usually bear cilia. The caecum of a living animal, just removed from the wood, was opened and the contents

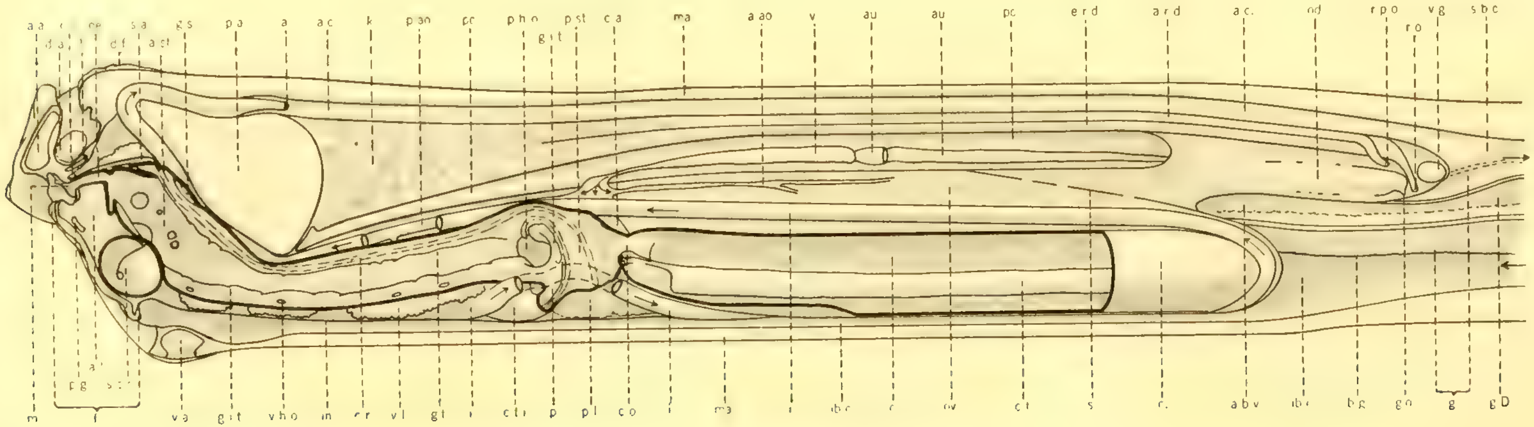
(*Continued on page 215*)

EXPLANATION OF FIGURE 77

1. Stereogram of *Teredo navalis*, anterior part, including the visceral mass, nearly all of the left half of the body having been removed to disclose structures lying in or near the sagittal plane. The anterior end of the animal is to the reader's left. The left half of the stomach, removed in this figure, is shown in figure 78, 1. Animals killed in alcohol have the foot completely retracted and all the drawings have been made with it in this condition. ×7.

2-5. Diagrammatic cross-sections at the levels indicated on 1. Anterior aspect.

a. Anus.
a.a. Anterior adductor muscle of the valves.
a.ao. Anterior aorta, homologous with the anterior aorta of other lamellibranchs, though running posteriorly in *Teredo*.
a.b.v. Afferent branchial vein, paired anteriorly, but single in the region of the gills.
a.c. Anal canal, a forward extension of the suprabranchial cavity.
a.l. Anterior liver.
a.r.d. Afferent renal duct (paired).
a.st. Anterior part of stomach.
au. Auricle of the heart. The left one is shown cut off close to the ventricle.
b.g. Branchial groove. One lies along each ventral edge of the gills, continuing forward on the side of the body to the labial palps.
c. Caecum of the stomach. In figure 1 the left wall is removed, except from the posterior fourth.
c.a. Caecal artery.
c.c. Cerebral commissure, connecting the cerebral ganglia, which are widely separated.
ci. Ciliated strip on the mantle.
c.o. Caecal orifice.
c.r. Ciliated ridge.
c.t. Caecal typhlosole.
c.t.i. Coiled typhlosole of the intestine.
d.a. Dorsal articulation, or pivotal knob, of the shell.
d.D. Duct of the gland of Deshayes.
d.f. Dorsal pallial fold.
e.r.d. Efferent renal duct (paired)
f. Foot.
g. Gill.
g.D. Gland of Deshayes in the gill lamellae. (Discovered and named by Sigerfoos, 1908.)
g.i.t. Gastro-intestinal typhlosole.
g.o. Right genital orifice.
g.s. Gastric shield. Only a small part of the right edge shows in figure 1.
g.t. Gastric typhlosole.
i. Intestine. The arrows point toward the anus.
ib.c. Infrabranchial cavity. The arrow indicates the direction of the flow of water.
in. Integument of the visceral mass.
k. Kidney, the tubular, spongy part of the excretory system.
l. Ligament of the shell.
l.c. Lateral canal. These are lateral, anterior extensions of the suprabranchial cavity, communicating with the infrabranchial cavity through the anterior gills (see fig. 76).
m. Mouth.
ma. Mantle.
od. Right oviduct.
oe. Oesophagus.
ov. Ovary. In male specimens the testes are similar in extent and relations (see fig. 79, 2-4).
p. Pylorus.
p.a. Posterior adductor muscle of the valves.
p.ao. Posterior aorta, homologous with the posterior aorta of other lamellibranchs, though running anteriorly in *Teredo*.
p.ar. Pallial artery, a continuation of the posterior aorta after it has looped over the posterior adductor muscle.
pc. Pericardium. Posteriorly it bifurcates, one auricle of the heart extending into each ramus and one afferent renal duct opening from each.
p.g. Pedal ganglia. The two are fused.
p.h.o. Posterior hepatic orifice.
p.l. Posterior liver.
p.st. Posterior, pyloric region of the stomach.
r.o. Right renal orifice.
r.p.o. Right reno-pericardial orifice.
s. Septum, separating regions that are probably homologous with the pedal and venous sinuses.
s.a. Supraoesophageal artery, a branch of the posterior aorta.
sb.c. Suprabranchial cavity. The arrow indicates the direction of the flow of water.
s.c.s. Sac of the crystalline style. Figure 1 shows the distal end from the inside.
st. Stomach.
v. Ventricle of the heart. The arrows at its anterior end indicate the direction of the flow of blood.
v.a. Ventral articulation, or pivotal knob, of the shell.
v.g. Visceral ganglia.
v.h.o. Ventral hepatic orifice. There are four of these, as shown in figure 1.
v.l. Ventral liver.



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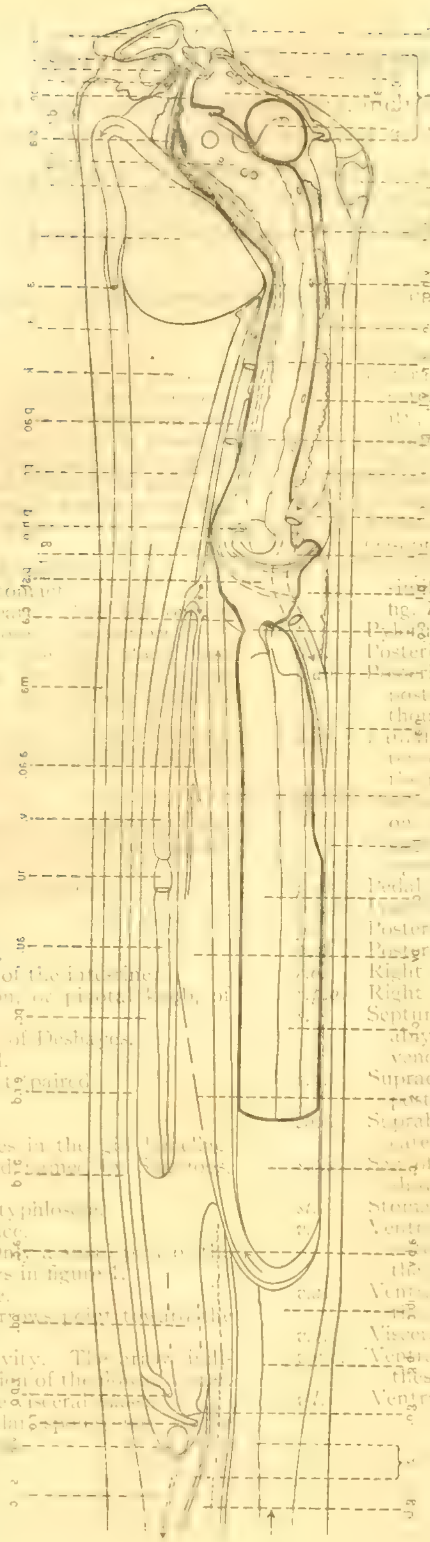

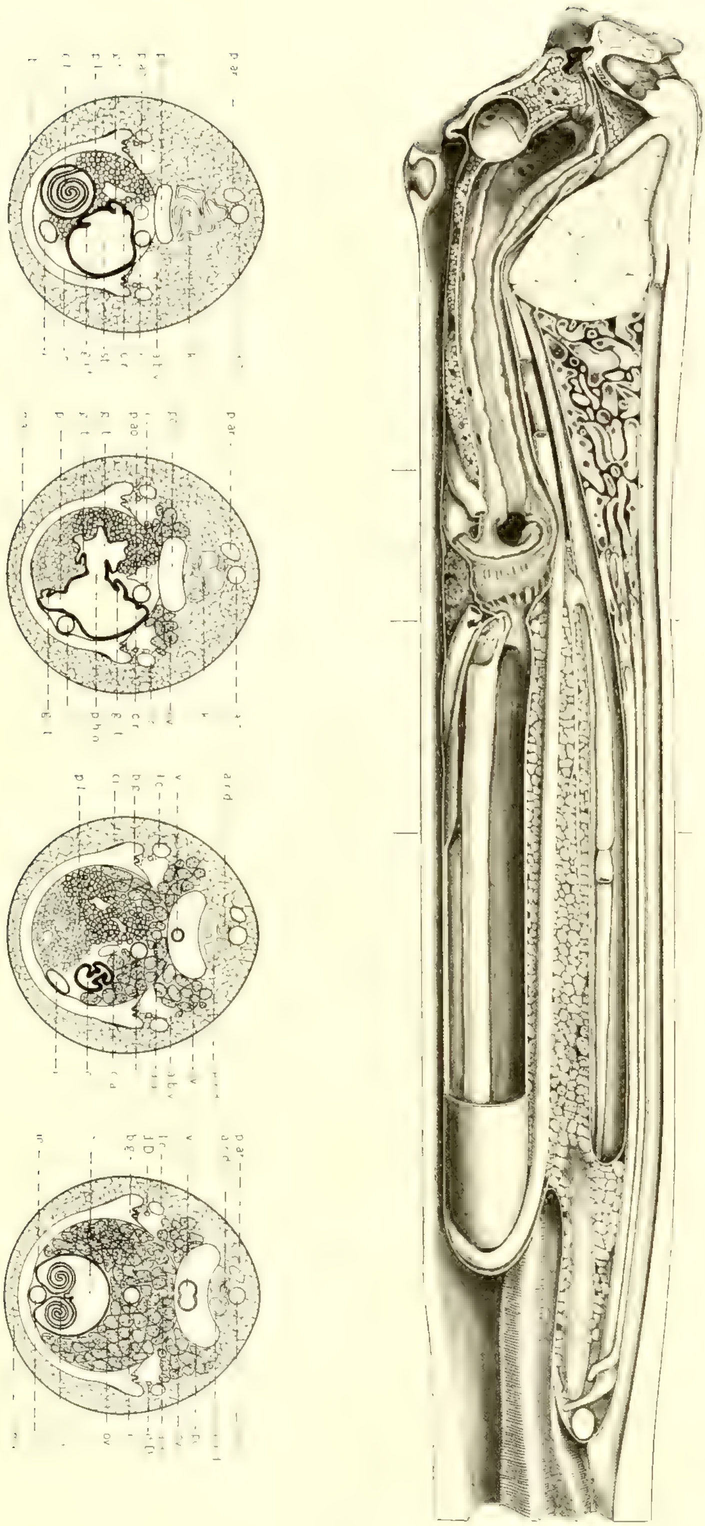

Fig. 77

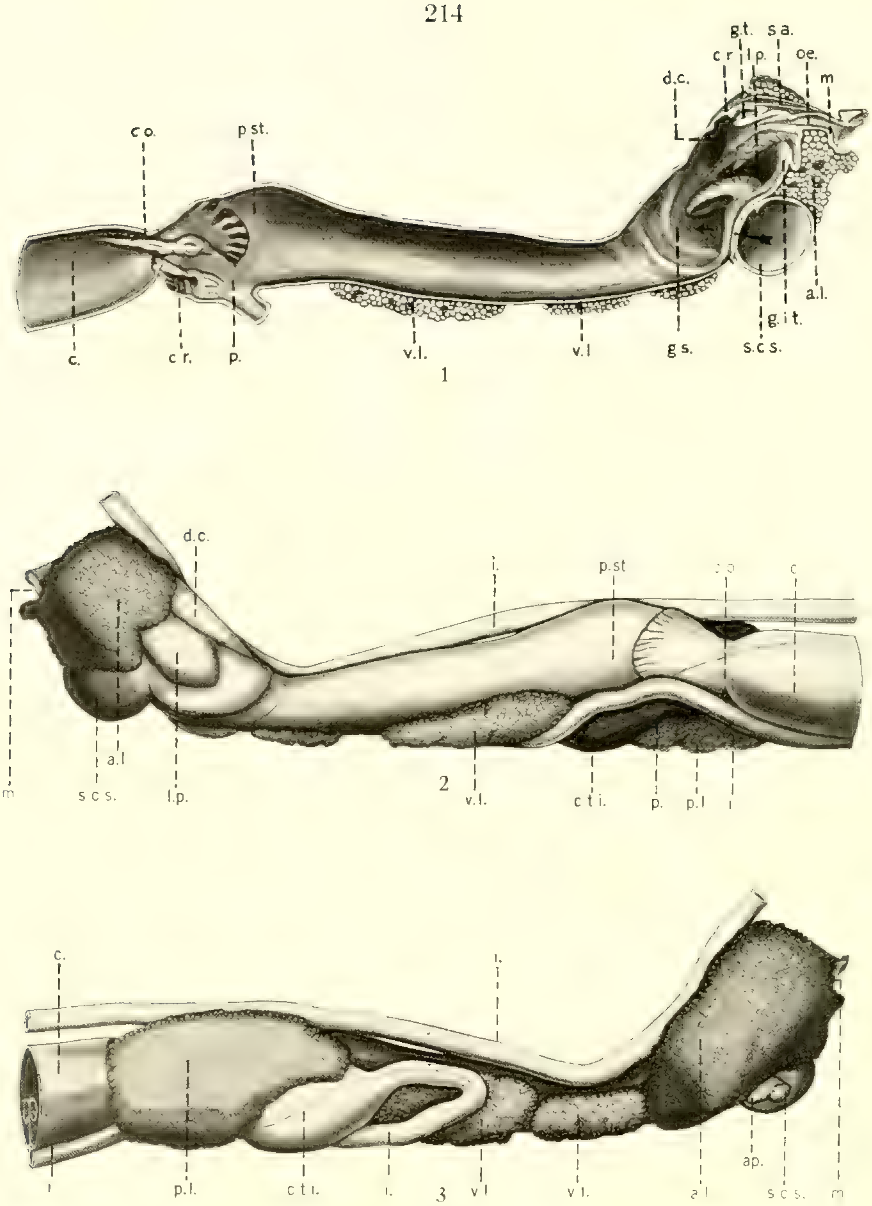

Fig. 78

1. Interior of the left half of the stomach, the part not shown in fig. 77. The arrow passes through the orifice of the sac of the crystalline style to the gastric shield.

2. Lateral, external view of the stomach from the left.

3. Lateral, external view of the stomach from the right.

All about x 7.

a.l.	Anterior liver.
ap.	Appendix of the sac of the crystalline style.
c.	Caecum.
c.o.	Caecal orifice.
c.r.	Ciliated ridge.
c.t.i.	Region of the coiled typhlosole of the intestine.
d.c.	Dorsal caecum.
g.i.t.	Gastro-intestinal typhlosole.
g.s.	Gastric shield.
g.t.	Gastric typhlosole.
i.	Intestine.
l.p.	Lateral pouch.
m.	Mouth.
oe.	Oesophagus.
p.	Pylorus.
p.l.	Posterior liver.
p.st.	Posterior, pyloric region of the stomach.
s.a.	Supraoesophageal artery.
s.c.s.	Sac of the crystalline style.
v.l.	Ventral liver.

were washed out with a pipette. Small quantities of mercuric sulphide and of fine carborundum dust were placed on various parts of the wall and on the typhlosole. There was no indication of any ciliary action, though such activity was very evident in other parts of the stomach and in the pallial cavity under like conditions. Slow writhing movements of the typhlosole were observed, however, and it is apparent that material is moved in and out of the caecum by muscular movements of the walls rather than by ciliary action. The experiment was repeated on several animals with similar results. This muscular movement approaching peristalsis is an unusual development in this order of lamellibranchs.

The orifice between the caecum and the stomach (*c.o.*) is incompletely divided into two openings by two lateral infoldings of the wall. The right fold is continuous with the caecal typhlosole. This arrangement probably provides for simultaneous ingress and egress of wood chips through the two divisions thus formed.

Deshayes (1848) and Quatrefages (1849) describe a caecum strikingly different from that described here and by other authors. Deshayes calls it the *second stomach*. It is thin walled, with a narrow orifice, and with a typhlosole ("valvule") like a funnel. This second stomach doubles back on itself and ends blindly. It is buried in brown hepatic tissue. The intestine takes off from it. Quatrefages goes into less detail in describing his species, but his figures indicate essentially the same structure. He denies, however, that the intestine leaves the caecum and believes this statement to be an error on the part of Deshayes.

The *sac of the crystalline style* (*s.c.s.*, figs. 77, 78) lies in a transverse position in the lower part of the foot, opening into the stomach on the left. The whole mechanism of the crystalline style is essentially similar to that described by Nelson (1918) for other lamellibranchs. The sac is pyriform and the interior is covered with the characteristic dense mat of long cilia. Extending from the mouth of the sac to its distal end is a small groove in the wall with a slight ridge on one side of it. The cells along this groove and ridge differ from those of the rest of the sac in that they stain deeply with Delafield's hematoxylin, are narrower, bear shorter cilia or none at all, and have their nuclei close to the basement membrane instead of near the center or toward the distal ends. From Nelson's descriptions of other species, we conclude that these cells are the ones which secrete the substance of the crystalline style. This groove terminates distally in the orifice to a small appendix to the sac. This appendix is termed by Sigerfoos (1908) the tubular part of the sheath of the crystalline style. Its thin walls are made up of non-ciliated cells similar to those in the secretory groove and ridge, and are continuous with them, indicating that it contributes to the formation of the style, as Sigerfoos suggests. A large fold of the epithelium overhangs the opening of the sac into the stomach.

The *crystalline style* itself is of the usual clear, gelatinous consistency. It is shaped like a heavy club, the smaller or "handle" end of the club projecting across the lumen of the stomach to the opposite wall where it bears against a structure which Nelson (1918) terms the *gastric shield*. This shield is a thin, transparent, cartilage-like plate secreted by the epithelium of the stomach. It may be dissected out or may be seen in microscopic sections. Its posterior and dorsal edges are marked by a faint ridge on the wall of the stomach. Ventrally it extends to the mouth of the sac of the style, and anteriorly it reaches into the lateral pouch and the dorsal caecum.

The observations we have recorded here agree in all essentials with Nelson's (1918) descriptions of species in which the sac is entirely separated from the intestine. He found that the style is rotated by the cilia lining its sac and that it is gradually dissolved away. It thus helps to keep in motion the contents of the stomach, and the

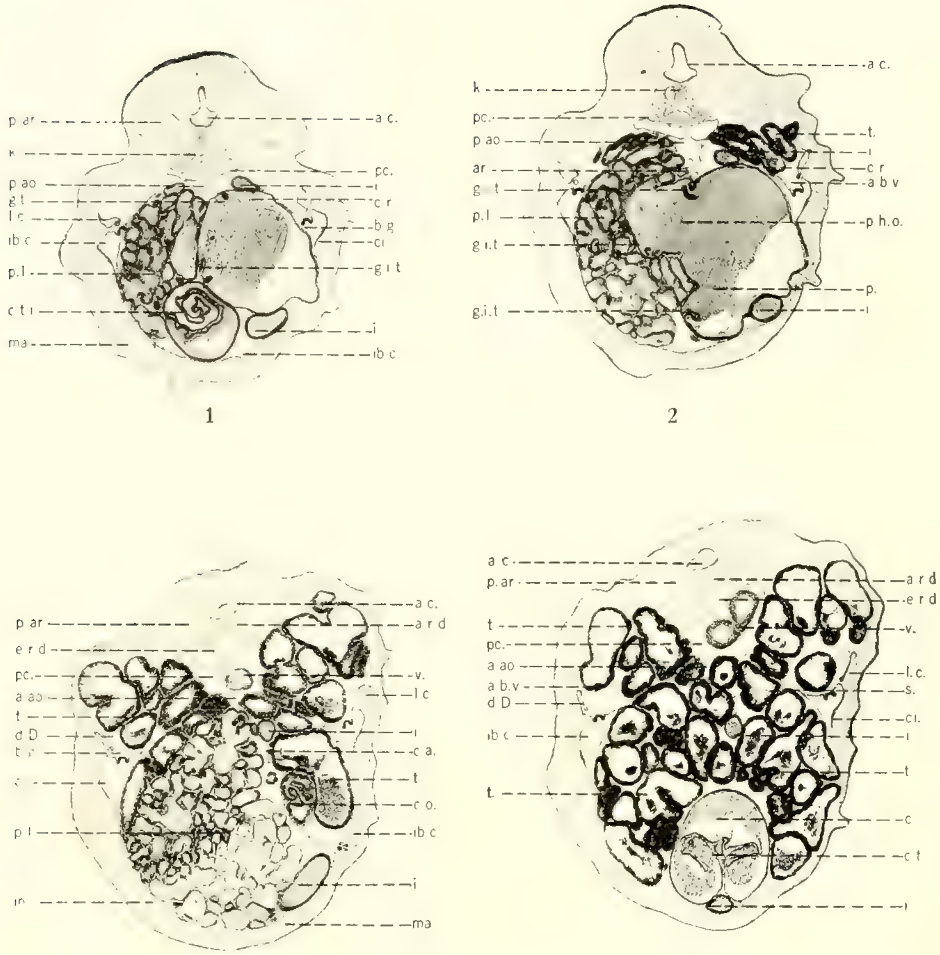

Fig. 79—*Teredo navalis L.*

Photomicrographs of cross-sections of a small male specimen, anterior aspect. These four figures correspond, respectively to figures 77, 2-5. Since the photomicrographs are of a smaller animal than that represented by the diagrams, the acini of the liver and the lobules of the gonad are relatively larger in the former. *Magnification 25 diameters.*

The specimen from which these sections were made was taken from a pile at Crockett, San Francisco Bay, on July 6, 1922. It was fixed in Gilson's fluid, imbedded in paraffin, the sections cut 10 microns thick, and stained in Delafield's haematoxylin.

a.ao. Anterior aorta.
a.b.v. Afferent branchial vein.
a.c. Anal canal.
ar. Artery to dorsal edge of hepatic orifice.
a.r.d. Afferent renal duct.
b.g. Branchial groove.
c. Caecum.
c.a. Caecal artery.
ci. Ciliated strip on mantle.
c.o. Caecal orifice.
c.r. Ciliated ridge.
c.t. Caecal typhlosole.
c.t.i. Coiled typhlosole of the intestine.
d.D. Duct of the gland of Deshayes.
e.r.d. Efferent renal duct.
g.i.t. Gastro-intestinal typhlosole.
g.t. Gastric typhlosole.
i. Intestine.
ib.c. Infrabranchial cavity.
in. Integument of the visceral mass.
k. Kidney.
l.c. Lateral canal.
ma. Mantle.
p. Pylorus.
p.ao. Posterior aorta.
p.ar. Pallial artery.
pc. Pericardium.
p.h.o. Posterior hepatic orifice.
p.l. Posterior liver.
s. Septum.
t. Testes.
v. Ventricle.

amylolitic ferments which it contains are set free to aid in digestion. The style of *Teredo* doubtless functions in a similar manner.

From the left antero-dorsal wall of the stomach projects a small, pointed diverticulum, the *dorsal caecum*. This caecum is ciliated internally. Between the dorsal caecum and the orifice of the sac of the crystalline style is a distinct outpocketing of the wall, which we have referred to as the *lateral pouch*. It is overhung by a peculiar roll of epithelium.

In lamellibranchs there is typically a typhlosole in the intestine extending more or less throughout its length, and as a rule, anteriorly into the stomach. In *Teredo navalis* this typhlosole, which we shall call the gastro-intestinal typhlosole, originates at the hepatic orifice in the lateral pouch, passes across the stomach below the opening of the oesophagus and posteriorly along the right ventral wall to the posterior hepatic orifice, which it enters. After circling the lumen of the posterior liver, it emerges at the dorsal edge of the orifice and passes posteriorly and ventrally into the intestine. Its fate there will be described in connection with the latter organ. From the hepatic orifice to the intestine, a small ridge lies opposite the free edge of this typhlosole. The gastro-intestinal typhlosole is ciliated throughout its entire length.

A second fold, which we may call the *gastric typhlosole*, originates in the dorsal caecum, passes above the opening of the oesophagus and, running parallel to the previously described typhlosole, extends to the posterior hepatic orifice, where it ends. A low ciliated ridge parallels its free edge and continues on above the hepatic orifice and down to end beneath the right one of the two folds lying in the caecal orifice.

Between this ridge and the one accompanying the gastro-intestinal typhlosole is a row of small transverse folds in the wall of the stomach. They extend from the posterior end of the gastric typhlosole to the fold under which the ciliated ridge ends. From the outer (left) fold in the caecal orifice, around to the right fold, in a spiral course, is another row of more pronounced wrinkles and pockets. The appearance of these on the outside of the stomach is shown in figure 78. The function of these two rows of irregular corrugations, which are of practically constant occurrence, is probably to increase the surface or the capacity of the stomach.

There is a small ridge, or lip, above and below the opening of the oesophagus into the stomach. The ventral one extends some distance to the left between the dorsal caecum and the lateral pouch.

Cilia do not cover the whole interior of the stomach as in more generalized bivalves, but are restricted to definite regions. The ciliated ridge and the gastro-intestinal typhlosole have been mentioned as being ciliated, but the ciliary mechanism of the alimentary tract has not yet been fully worked out in *Teredo* as it has been by Nelson (1918) in several other forms. A few observations on living animals, however, have shown strong localized ciliary currents, and further investigation will probably disclose an elaborate mechanism for handling and sorting food homologous with that found in other species. The method of manipulating the wood chips which are ingested would of itself be an interesting discovery.

The intestine, from its origin at the stomach, runs anteriorly a short distance and bends sharply upon itself. Its course is then back, remaining ventral, to the posterior end of the caecum, up around the latter and forward through the gonad, passing to the left of the caecal artery, and posterior aorta. It goes under the posterior adductor muscle, bending a little to the left and then back to the mid-line, and ends on the dorsal side of this muscle in the anal canal. The intestine is not as straight as it is shown in the stereogram, but it makes no extensive convolutions or bends other than those indicated.

The gastro-intestinal typhlosole enlarges in the intestine a short distance from the stomach, and coils to the right, forming the large *coiled typhlosole of the intestine* (*c.t.i.*, figs. 77, etc.). It then again resumes its former size and continues to the sharp bend in the intestine. From here to the anus the typhlosole is entirely absent.

Figure 78 shows the dilation of the intestine to two or three times its diameter elsewhere for the accommodation of this unique structure. In this same figure can be seen the line where the intestinal wall folds in to form the typhlosole. At the distal end of the rectum are a few strands of sphincter muscle. The intestine is ciliated throughout.

Sigerfoos gives a similar description, but in his species a small typhlosole extends throughout the whole intestine. Deshayes and Quatrefages describe the intestine as being of uniform diameter throughout, indicating the absence of a coiled typhlosole. At the same time the intestine is longer and much convoluted, though its general course through the body is similar. These two distinct types of intestine are easily observed, and should prove of systematic value. The consideration of such internal characters may shed some light on the badly tangled taxonomy of the group.

The intestine is always found to be full of wood chips and the remains of diatoms and other plankton organisms. In a piece of intestine removed from a small living Teredo the contents were observed to move posteriorly about one millimeter in two minutes as the result of ciliary action.

THE CIRCULATORY SYSTEM

The pericardium of *Teredo* is much elongated, extending from the posterior adductor muscle to a point some distance back of the posterior extremity of the caecum. The *heart*, which occupies a median position in this cavity, is composed of two elongated auricles and an elongated muscular ventricle. In a living specimen the pulsations of the heart can be plainly seen through the transparent tissues of the body wall.

Each of the auricles receives from behind one of the paired *efferent branchial veins*. From these aerated blood from the branchial region enters the auricles, whence it passes to the ventricle and is pumped into a large aorta. This vessel passes ventrally through the floor of the pericardium, and immediately divides into three branches. As has been previously explained, the morphological relations of the circulatory system have been reversed by the partial rotation of the heart and pericardium around the posterior adductor muscle. Hence, what is morphologically the *anterior aorta* passes backward to carry a blood supply to the visceral mass. A second vessel, morphologically the *posterior aorta*, passes forward, under and around the posterior adductor muscle, and enters the mantle. It then continues backward as the *pallial artery* to the base of the siphon, where it divides, furnishing a blood supply to each. The third, which may be termed the *caecal artery*, drops immediately and enters the anterior end of the caecal typhlosole. After passing through the typhlosole, the blood flows into the sinuses in that part of the body.

The circulation of blood in the various parts of the digestive tract is still to be worked out in detail, but one or two major points may be mentioned. The whole tract, including the livers, is evidently bathed in blood carried in sinuses with connective tissue walls (Pelseneer, 1906). The typhlosoles, however, have a definite arterial supply. That of the caecal typhlosole has been described. A small branch from the posterior aorta (fig. 77) supplies the gastro-intestinal typhlosole at the bend of the intestine where the typhlosole ends. Another small branch (*a.r.*, fig. 79) goes to the dorsal edge of the posterior hepatic orifice, probably supplying the gastric typhlosole.

Blood from the anterior portion of the body and the sinuses mentioned above is gathered by a system of afferent branchial veins, consisting (Sigerfoos, 1908) anteriorly of two vessels, which fuse in the region of the visceral ganglion to form a single large *afferent branchial vein* (*a.b.v.*, figs. 77 and 79). This vessel extends posteriorly, occupying a median position between two gills. From it blood passes into the gill filaments, where it becomes oxygenated and then passes into the *paired efferent veins* mentioned above, which lead it once more to the auricles of the heart. Thus the circulation is completed.

This description of the circulatory system applies to *Teredo navalis*, and also, according to Sigerfoos (1908), to *Bankia gouldi*. There is, further, according to the statement of this author, an afferent renal vein in the mantle, to the left of the epibranchial canal, which gathers blood from the posterior part of the body and carries it forward to the perinephridial spaces at the posterior end of the kidneys.

THE RESPIRATORY SYSTEM

The greater portion of the length of *Teredo* is occupied by the gills. These consist of paired lamellae which extend forward from the base of the siphons, dividing the mantle cavity into a ventral or *infrabranchial cavity* and a dorsal or *suprabranchial* cavity. The gill lamellae are made up of hundreds of transverse filaments, which are fused at their bases and united at intervals for the remainder of their length by supporting connectives or *interfilamentar junctions*. Thus the gills form a sort of trellis work which permits a free passage of water among the filaments.

In cross section each gill resembles a letter V with the apex directed lateroventrally. Thus, taken together, the two gills in cross section roughly resemble the letter W. If now a circle were placed about the W to represent a cross section of the mantle of *Teredo*, the space below and to the sides of the W would represent the infrabranchial cavity, and the space above the W the suprabranchial cavity. The space included by the outer limbs of the W would be occupied by a structure known as the *gland of Deshayes*, and by the intrapilamentar blood spaces.

In typical forms, like *Mya*, the gill of each side consists of two V's, or a W. Sigerfoos (1908), from his observations on the developing teredinid larva, concluded that the gills of *Teredo* correspond to the inner V of each gill of *Mya*, the outer member never developing.

OTHER ORGAN SYSTEMS

The *nervous system of Teredo* is essentially that of the usual lamellibranch type, with modifications due principally to the elongation of the body of the animal. The paired *cerebral ganglia*, lying just above and at each side of the mouth, are connected by a long, narrow *cerebral commissure*. The *pedal ganglion* (*p.g.*, fig. 77), which lies in the dorsal part of the foot, just below the oesophagus, is composed of two elements morphologically which are closely fused into one. The pedal and cerebral ganglia are connected by the usual *cerebro-pedal* connectives, one on each side of the oesophagus. The *visceral ganglion*, likewise composed of two major elements fused into one, lies at the posterior end of the visceral mass, instead of under the posterior adductor muscle as in the more typical eulamellibranchs. The visceral ganglion is connected with the cerebral ganglia by a pair of *cerebro-visceral connectives*, which anteriorly are widely separated, each occupying a lateral position just underneath the anterior gills, but posteriorly approach each other and occupy a more nearly median position as they pass through the visceral region.

Just anterior to the visceral ganglion is a small ganglionic mass which has been

rather misleadingly named the *anterior ganglion*. This structure is apparently peculiar to the shipworms and closely allied forms. The cerebro-visceral connectives give off a few fibres to this ganglion as they pass dorsal to it just before entering the visceral ganglion.

From the outer side of each of the cerebral ganglia a *pallial nerve* passes into the mantle, supplying the anterior portion of the mantle and the cephalic hood. From the pedal ganglion several pairs of nerves are given off which innervate the foot. From the anterior ganglion, according to Sigerfoos (1908), nerves are given off to the kidneys and other viscera, and to the *osphradia*. These last are organs of special sense, peculiar to lamellibranch mollusks, which lie at each side of the visceral ganglion, and are presumed to have the function of testing the water which passes over the gills.

From the visceral ganglion nerves are given off which pass forward to the large posterior adductor muscle and the anterior part of the mantle, others which innervate the middle part of the mantle, and another large pair of *pallial nerves* which pass posteriorly into the mantle and finally innervate the muscles of the pallets and the siphons. On either side of the visceral ganglion a *branchial nerve* is given off which passes into the gills.

The *excretory organs* of *Teredo* are a pair of greatly elongated kidneys (*k.*, fig. 77), which lie dorsal to the pericardium, between it and the anal canal. Each kidney is essentially a long tube which extends forward from the posterior end of the pericardium to the region of the posterior adductor muscle, and is then doubled back upon itself and extends posteriorly to a point near its origin, where it empties into the suprabranchial cavity.

In the region between the posterior adductor muscle and the heart this double tube is elaborated into a many lobed or pouched glandular structure which forms the body of the kidney. The portion of the tube leading forward to this from the pericardial cavity is termed the *afferent renal duct*, and the opening by which it is connected with the pericardial cavity is known as the *renopericardial orifice* (*r.p.o.*, fig. 77). The portion of the tube leading posteriorly from the body of the kidney, the *efferent renal duct*, empties into the suprabranchial cavity through the *renal orifice* (*r.o.*, fig. 77).

All these structures are paired. Thus there are two afferent and two efferent ducts which parallel each other, and the orifices mentioned are likewise paired.

The sexes of *Teredo*, as our observations indicate, are separate. Sigerfoos (1908) reports finding small hermaphroditic specimens of *Bankia gouldi*, and suggests that this species may be protandrous (i. e., male when young, later becoming female), as in such cases observed by him the sperms are developed first. Yonge (1926a) has recently reviewed the question and from his investigations of *Teredo norvegica* concludes that this species, at least, is protandrous. Our limited observations on the matter are not contrary to the same view in regard to *Teredo navalis;* the male specimens are commonly smaller than the females; but definite proof of change of sex is lacking.

The reproductive organs, the ovaries of the female and the testes of the male, lie dorsal to and at each side of the caecum. During the breeding season the ovaries of the female become greatly enlarged, nearly surrounding the pericardium and the caecum, and the hundreds of separate lobules are densely packed with eggs.

The eggs, when ripe, are extruded from the genital pore, and in most species of *Teredo* they enter the gills, where fertilization takes place by the agency of spermatozoa that are taken in with the water of the respiratory current.

A special brood pouch is developed within the "V" of each gill by a thinning and partial fusion of the filaments, and in this the larvae are retained until they reach

a rather advanced stage of development, when they are extruded as minute, free-swimming bivalve larvae, to be distributed far and wide by tides and currents.

According to Hatscheck (1881), who has studied the larval development of *Teredo* in greater detail than any one else, the larvae enter the gills of the parent from the posterior end, so that the most advanced embryos are found in the anterior portion of the gills. Exactly what occurs in this connection has never been found out. The embryos are probably nourished from the blood of the parent, of which the gills have an abundant supply.

In some species of *Teredo*, such as *T. norvegica*, and in all forms of *Bankia* of which the breeding habits are at all known, no brood pouch is developed, but the eggs apparently are extruded into the water, where they depend on chance fertilization, and the larvae during their entire development are subjected to the vicissitudes of pelagic life. This must mean a greatly increased coefficient of fatalities among the larvae, any individual egg having a much slighter chance of fertilization, and still less of reaching maturity, than is the case in the forms which retain the developing larvae in the gills. This doubtless explains the fact that *Bankia* is ordinarily less numerous than the incubatory species of *Teredo*.

CHAPTER XV

THE BORING HABIT

The method by which the smooth walled, perfectly rounded burrows of *Teredo* are excavated has excited considerable interest over a long period of time. As early as the first century A. D. the Roman naturalist Pliny the Elder remarked upon it. His conjecture that boring is accomplished by means of the shell appears to have gone unchallenged until 1733, when the Dutch investigator Sellius objected that the shell of *Teredo* does not appear adequate to the task of boring, especially in hard woods, such as oak. He believed the boring to be accomplished by a kind of suction with the foot, aided by the action of the water which is taken into and forced out of the burrow.

The opinion of Sellius precipitated a discussion which has been carried on intermittently for nearly two hundred years. While a majority of writers have favored the view that boring is carried on by movements of the shell, not a few have insisted that the burrows are excavated by a slow but continuous wearing away of the wood by friction and suction with the foot. Proponents of the latter theory have stated that the shells are inadequate to boring, that they do not show signs of wear as would be expected if their function were that of rasping wood, that certain forms such as the limpets are known to excavate depressions in rocks by means of the foot, and that the walls of the burrow of *Teredo* are too smoothly polished to have been rasped mechanically. It is only recently, in this investigation (Miller, 1924a), that the question has been definitely decided, observations of animals in opened burrows having shown that boring actually is accomplished by the shell, as Pliny had long ago conjectured.

The Method of Boring

Corresponding to its unusual function, the shell of *Teredo* has been specialized in a very remarkable way. Although the organism is anatomically quite closely related to the common soft shell clam, the early naturalists are hardly to be blamed for placing it in an entirely different group. The shell of the adult *Teredo* has been reduced, relative to the size of the animal, until it covers only a small portion of the anterior part of the body, the much elongated visceral and branchial portion protruding posteriorly, and having as its protection the smooth, nacre-lined walls of the tapering burrow. The shell itself is an irregularly shaped, sub-globular structure, consisting of two valves, united dorsally by a reduced ligament. The valves gape widely in front (fig. 80) for the protrusion of the foot, and somewhat less widely behind for the backward extension of the long, slender body.

The terminology used in discussion of the shell has been explained in an earlier chapter and illustrated by the diagram, figure 68, to which reference should again be made.

The ridges of both the anterior and anterior median areas are equipped with specialized denticles. Those of the anterior lobe are merely fine serrations along the summit of each ridge. The denticles of the anterior median area, however, are rather intricately sculptured, wedge-shaped structures, the points of which are directed outward and backward. They are on the whole regularly spaced, and are much larger and coarser than the denticulations of the anterior lobe. The latter act as the advance boring edges, working in the extreme end of the burrow, while the coarser denticles of the anterior median area work peripherally with a reaming action, enlarging the

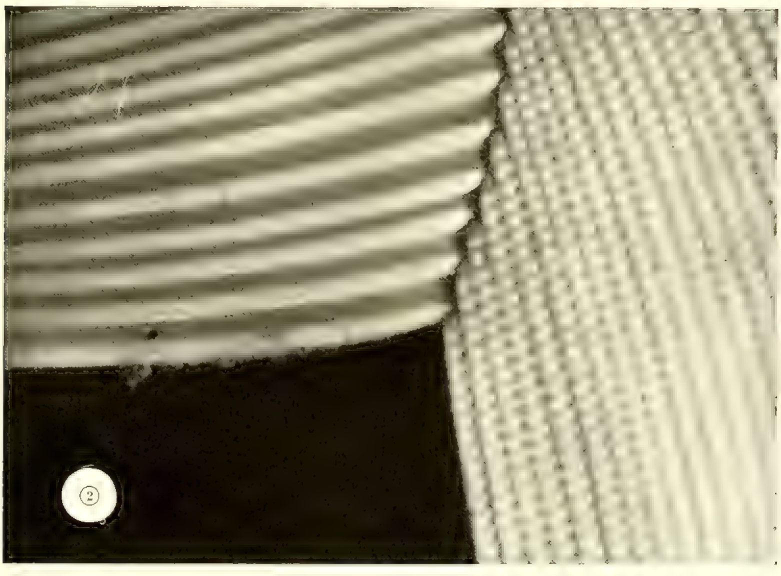

Fig. 80

1. Anterior view of *Teredo navalis*, showing relations of shell and foot. The translucent marginal web of tissue encircling the aperture of the shell is the inner free fold of the mantle. x 10.

2. Detail of surface sculpture of the shell of *Teredo navalis*, in the region of the angle formed by the juncture of the finely serrate ridges of the anterior lobe (left) with the coarsely denticulate ridges of the anterior median area (right). x 50.

diameter of the burrow. Thus the external sculpture of the shell is adapted in detail to its peculiar function of boring in wood.

The two valves are in contact with each other dorsally and ventrally by two specialized knobs. The anterior and posterior adductor muscles (fig. 81), opposing each other, enable the shells to rock back and forth upon these two points of contact, executing a movement about the dorso-ventral axis, instead of the simple opening and closing movements of which alone most bivalves are capable. Thus a relatively slight modification of the shell enables *Teredo*, without change of musculature, to execute an entirely new movement. The valves of the shell are able to move back and forth with the alternate contractions of the anterior and posterior adductor muscles, somewhat like the jaws of a clam-shell dredge. The edges of the valves, of course, are never brought together, but gape widely in front to permit the protrusion of the foot even when the anterior adductor is tightly contracted. The movement of the valves is limited, the edge of each one being able to describe an arc of from twenty to thirty degrees, varying somewhat with the individual specimen.

With this understanding of the method of movement of the shell, the reason for the peculiar development of the auricle becomes apparent; its purpose is to serve as an attachment for the posterior adductor muscle, which is thus able to function more efficiently because of the increased leverage obtained by means of this backward extension of the shell. The margin of the auricle is usually slightly flexed outward, so that its edges do not cut sharply into the viscera when the backward margins of the valves approach each other on contraction of the posterior adductor.

The posterior adductor is a large, powerful muscle, which has its attachment over nearly the entire inner surface of the auricle. Its structure is exceedingly firm and compact, fitting it to exert a strong tension on the shell. In sagittal section (fig. 81) the area of the posterior adductor is nine times that of the anterior adductor. Near its attachment to the shell the posterior adductor becomes expanded, so that in cross section its area may be as much as thirteen times that of the anterior muscle. As the length of the posterior adductor in the contracted state is about three times that of the anterior adductor, its volume is accordingly at least thirty times that of the latter. The coarse, granular nature of the posterior muscle and, in the living animal, its distinctly reddish color, indicate that it is adapted to perform powerful contractions. In general, muscles which perform repeated and strong contractions are darker in color than other muscles, a typical example of this being the vertebrate heart.

The great development of the posterior adductor of *Teredo* relative to the size of the shell is seen from figure 82, in which the areas of attachment of the shell muscles of *Teredo* are compared with those of *Mya*.

The foot of *Teredo*, although not, as some have supposed, the actual tool of boring, nevertheless plays an important role in the boring process. This organ, in a contracted state, as seen in figure 80, is a subcircular disc, the periphery of which is thrown into folds and is raised somewhat above the plane of the central area. A median notch in this wrinkled periphery, dorsal and ventral, marks the division between the muscle insertions of the right and left sides.

In sagittal section (fig. 81), several differences are to be noted between the central disc of the foot and this peripheral area. The former is relatively smooth, non-ciliated, non-glandular; the latter is folded and wrinkled, strongly ciliated, and characterized by numerous close-set, deeply staining gland cells. The interior of the foot, with the exception of the muscular portion discussed below, is of an open, spongy texture, made up of loosely arranged connective tissue cells which permit an easy movement

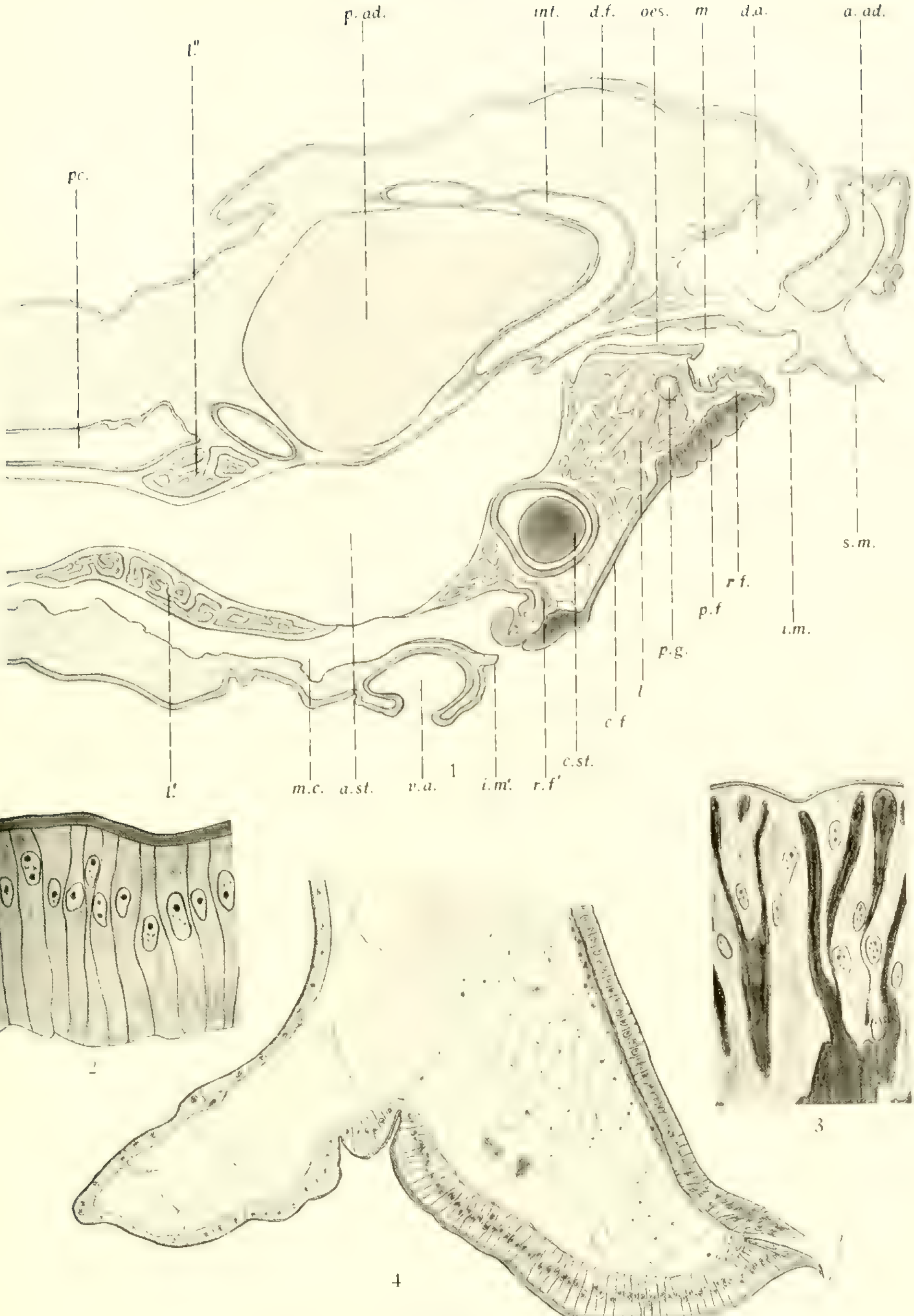

Fig. 81

1. Anterior end of *Teredo navalis* in sagittal section. Camera, x 25. *a.ad.*, anterior adductor muscle; *a.st.*, anterior part of stomach; *c.f.*, central disc of the foot; *c.st.*, crystalline style; *d.a.*, pocket of the dorsal articulation of the shell; *d.f.*, dorsal fold of the mantle; *i.m.*, *i.m.'*, inner free fold of the mantle; *int.*, intestine; *l.*, *l.'*, *l.''*, livers; *m.*, mouth; *m. c.*, mantle cavity; *oes.*, oesophagus; *p.* ad., posterior adductor muscle; *p. c.*, pericardial cavity; *p. f.*, peripheral area of the foot; *p. g.*, pedal ganglion; *r. f.*, *r. f.'*, retractor muscles of the foot; *s. m.*, secreting border of the mantle; *v. a.*, pocket of ventral articulation of the shell.

2. Detail of epithelium of the central disc of the foot. Camera, x 750.

3. Detail of epithelium of the periphery of the foot. Camera, x 750.

4. Detail of cross-section through anterior termination of mantle (*i.m.*, *s.m.*, fig. 1). Inner, free fold (left), and outer secreting fold (right), showing insertion of periostracum. Camera, x 175.

of body fluids among them for the purpose of modifying the turgor of the foot in process of extension or retraction.

The muscles of the foot consist of a pair of anterior retractors, a pair, or rather a series, of posterior retractors, and a pair of protractors. The anterior retractors, extending dorsally from the foot, have their insertion in the anterior umbonal region of the shell. The posterior retractors, extending as wide, semicircular bands from the margins of the foot, are attached to the apophyses, which, extending ventrally from beneath the dorsal knobs of the shell, almost encircle the foot. The protractor muscles, which function in extending the foot by compressing the anterior portion of the body, have their insertions near those of the anterior retractors. Their relatively small size as compared with the wide bands of retractors, suggest that the foot is extended as much by turgescence as by muscular action.

In specimens of *Teredo* removed from their burrows and kept in open dishes in the laboratory, the foot has sometimes been seen distended to a distance of two or three millimeters beyond the margins of the shell, and extremely turgid, so as to be almost transparent. Different areas of the foot appeared to be independently movable, so that the organ could be compressed on one side and expanded on the other or rolled about somewhat amorphously, and extended in any direction. All the movements observed were such as could be produced by the combined action of turgor and contraction of the semicircular bands of retractor muscles.

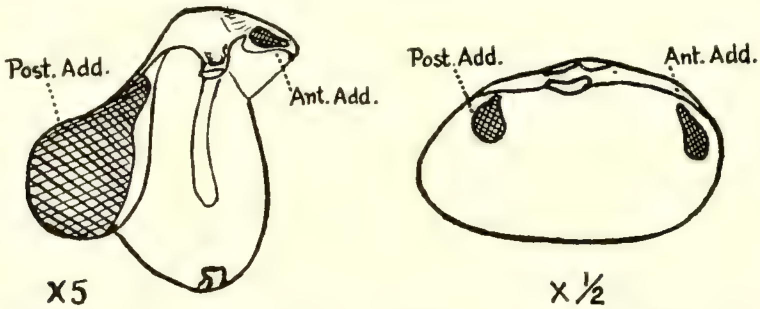

Fig. 82. Relative areas of attachment of the anterior and posterior adductor muscles of *Teredo navalis* (left), and *Mya arenaria* (right).

In order to determine if possible by direct observation the movements involved in boring, the experiment was tried of opening a burrow carefully near the anterior end and sealing over the opening a glass cover-slip, thus making a small window in the burrow, through which the movements of the occupant could be observed with the aid of a binocular microscope and a narrow shaft of light. Most of the animals disturbed in this fashion would retract about a third of the length of the burrow, so that they were entirely out of sight from the window, and after a few days' quiescence they would bore off in another direction. But after a number of repetitions the experiment finally proved successful. One specimen was found which carried on boring operations directly in view of the small glass window, and the process was observed in considerable detail.

The boring is accomplished by rasping with the valves, which are held in position by the combined action of the foot, attached to one wall of the burrow, and the dorsal fold of the mantle, distended by turgor, pushing against the opposite wall. The typical boring position is seen in figure 83 (*cf.* also figure 84, *1* and *2*).

At each stroke of the valves the foot takes a new hold. The effective stroke of the valves is the outward and backward one. This had been already assumed from the

direction of the points of the denticles on the shell, and from the extraordinary development of the posterior adductor muscle. As the backward stroke of the valves is completed, the foot is relaxed and its margins spread out so far that they overlap the edges of the shell. Then, by a sudden contraction, the margins of this structure are drawn in and the valves brought forward into position for a new stroke. Then follows the slow, labored contraction of the large posterior adductor, causing the forward edges of the valves to spread apart and rasp the wood by their outward thrust. That the valves do actively scrape the wood on this stroke is indicated by the fact that they were observed frequently to slip, the backward margins being drawn together with a jerk instead of the usual slow, steady pull.

The boring movements occurred rhythmically, from 8 to 12 times a minute. It was not possible to measure accurately the length of the stroke, but experiments on other individuals have shown that the maximum stroke possible allows the forward edge of each valve to move through an arc of from 20 to 30 degrees.

The anterior tip of the burrow is mined out by the anterior lobe of the shell; the movement of the shell is necessarily in a direction longitudinal to the ridges of this area, so that their serrate edges act upon the wood as so many small saws. It will be recalled that the serrations on the ridges of the anterior area are extremely fine (fig. 80) as compared with the denticulations of the anterior median, and hence better fitted to act as the advance boring edges. Also the shape and position of the anterior lobe especially adapt it to working in the extreme tip of the cupped end of the burrow. The marks of the work of the anterior lobe of the shell are often plainly evident on the wood (figs. 84 and 85).

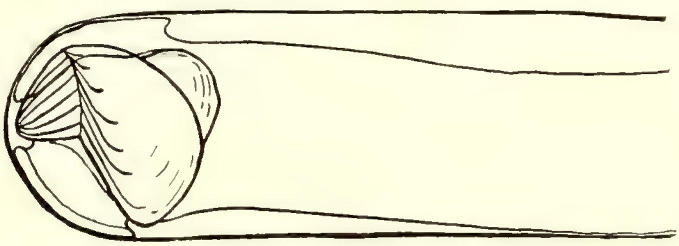

Fig. 83. Boring position of *Teredo* in end of burrow.

While the ridges of the anterior lobe are working saw-fashion in the tip of the burrow, the coarser wedge-shaped teeth of the anterior median area are at the same time working rasp-like, enlarging the diameter of the burrow and advancing the peripheral portion of its cupped extremity. Thus, while the tools might be compared to saw and rasp, their work is in effect that of a drill and reamer. The marks of the work of the anterior median area are rarely to be distinguished clearly, owing, no doubt, to a tendency of the coarse, close-set denticulations of this area to abrade and tear the macerated surface of the wood rather than to leave a clean-cut impression, as do the finely serrate ridges of the anterior portion of the shell.

The disposal of the rasped-off particles of wood it was not possible to observe, because of their minute size. There is, however, every reason to believe that it is the function of the cilia of the periphery of the foot to sweep these particles up and into the range of the cilia of the oesophagus. Apparently all of the rasped-off wood passes through the digestive tract, which is continually found to contain wood particles in considerable quantities.

It was observed in studying the particles of wood in the digestive tract that these are of two sorts. Large particles stand out conspicuously, from 0.30 to 0.40 mm. in

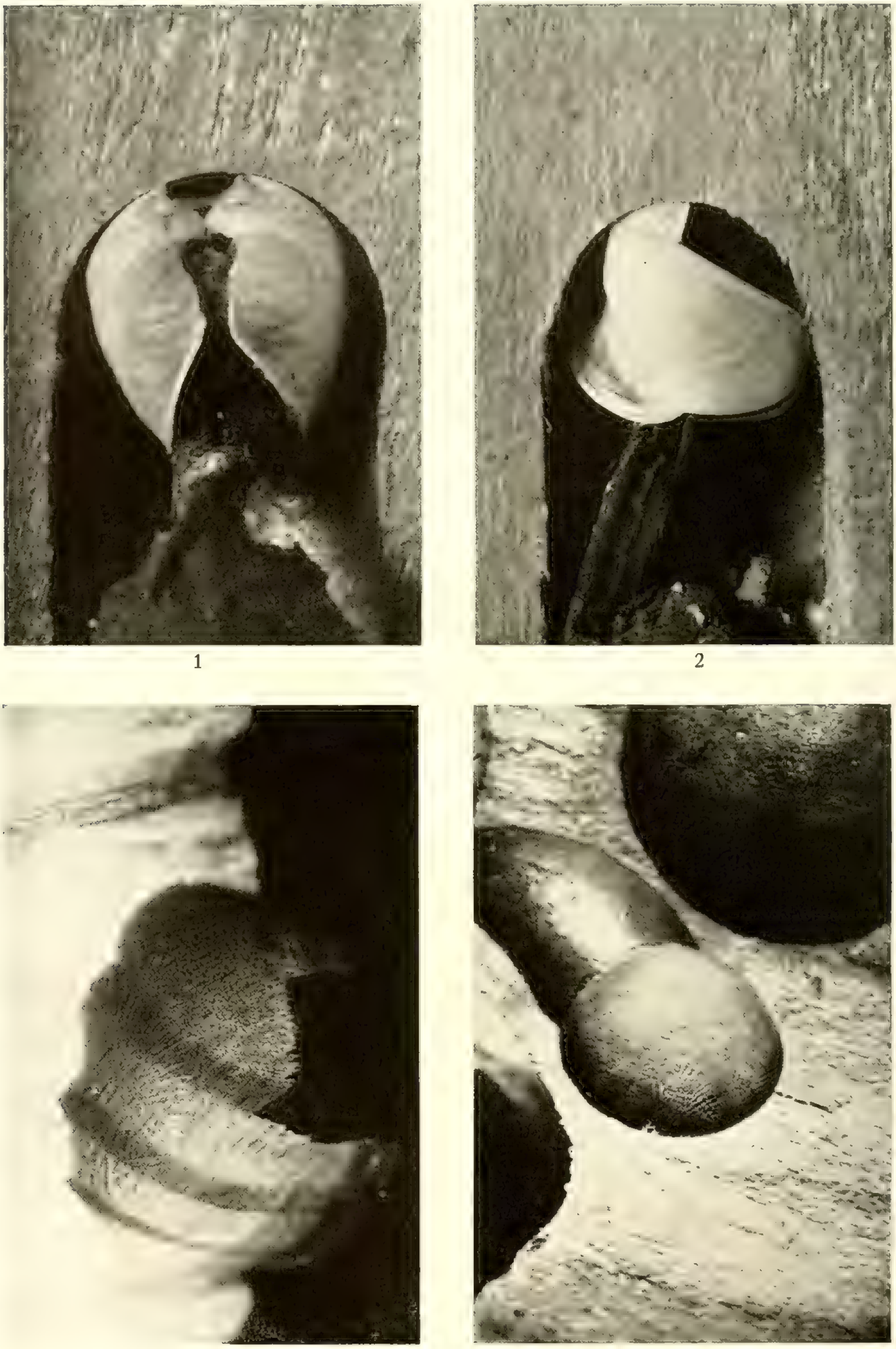

Fig. 84

1. Shell of *Teredo navalis* mounted in position at end of burrow, dorsal view. x 10.
2. Shell of *Teredo navalis* mounted in position at end of burrow, lateral view. x 10.
3. Cupped extremity of a burrow of *Teredo navalis*, showing markings made by the shell. x 10.
4. Same, smaller specimen.

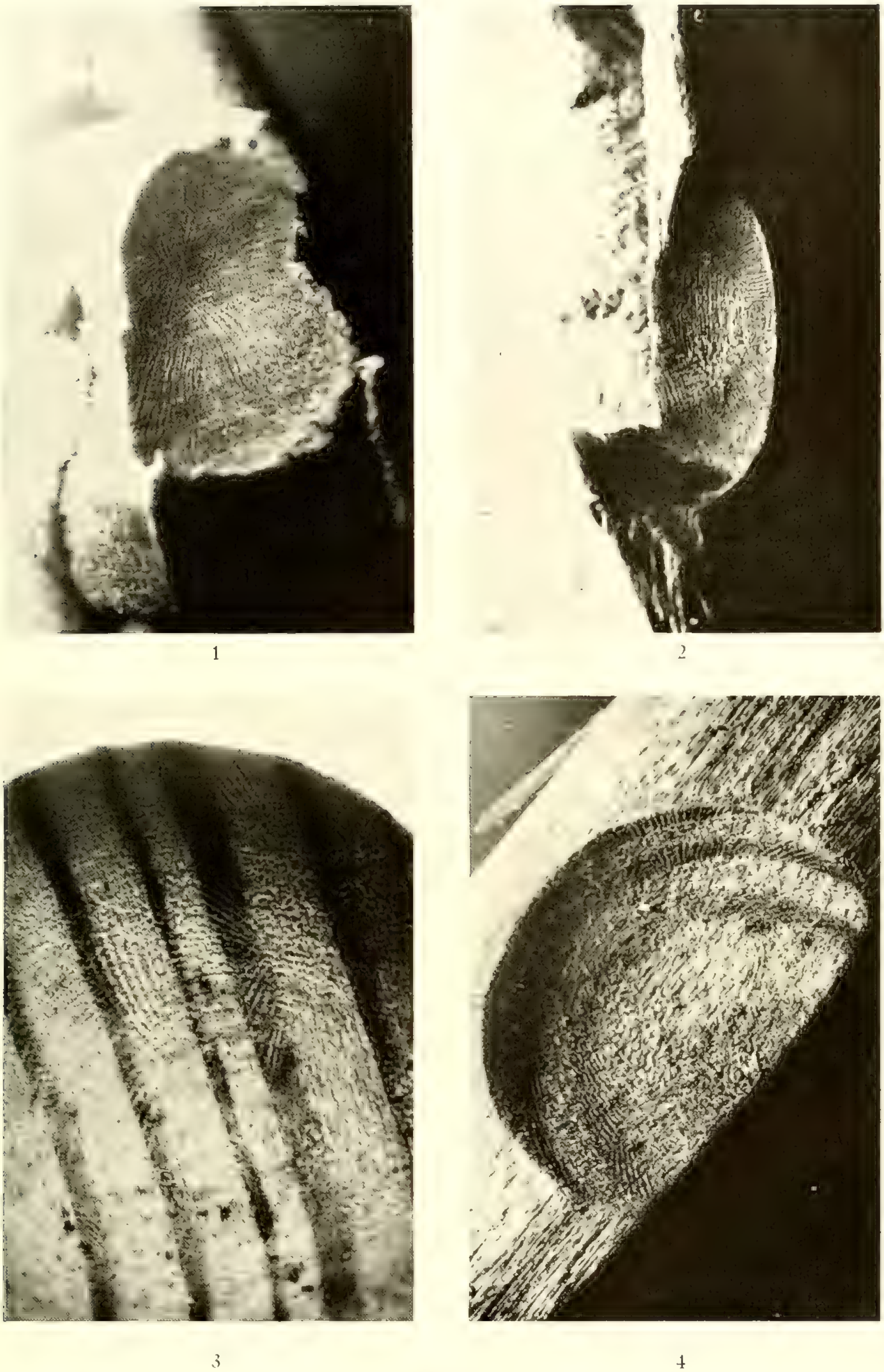

Fig. 85

1. Cupped extremity of a burrow of *Teredo diegensis*, showing markings made by the shell. x 10.
2. Same, *Teredo affinis*. 3. Same, *Bankia setacea*. 4. Same, *Bankia mexicana*.

length, and from 0.02 to 0.08 mm. across. On the other hand, minute particles 0.02 mm. or less in length and of about the same breadth, occur numerously. While many particles of intermediate size indeed occur, one is able to differentiate readily the two classes of particles; elongate, fibrous ones and fine, granular ones. The conclusion immediately suggests itself that the latter are produced by the fine serrations of the anterior lobe of the shell, while the former are rasped off by the coarser denticulations of the anterior median area.

The position assumed by *Teredo* in boring off at a right angle to its former direction of progress is seen in figure 86. One would hardly have supposed that such an awkward position is assumed by the animal in changing the course of its burrow, were this not actually a matter of observation. Apparently the valves function without difficulty under such circumstances. This explains how *Teredo* is able to make the abrupt changes in the course of its burrow which are so often found, especially in heavily riddled piling, where such changes of direction are necessary in order to avoid breaking through into neighboring burrows.

Fig. 86. Boring position of *Teredo* beginning a side passage at a right angle to former course of burrow.

The commonly made statement that one teredo will never bore into or cross the burrow of another is not, strictly speaking, true. Occasional instances have been found in which one burrow passes directly through another. Such cases are rare, however, and it is probable that the first animal was dead before the second entered its burrow, as otherwise it would doubtless have been able to protect itself by a thickened wall of nacre. In heavily riddled timbers the teredos will sometimes adopt unusual expedients, such as to cross a crack of considerable magnitude in order to find new wood to attack. One instance was observed in an aquarium where a teredo had bored completely through a piece of wood, so that its shell and the anterior part of the body protruded into the water. This animal was doubtless abnormal.

The foot appeared, from observation, to be an organ of sense and a means of limited locomotion about the narrow confines of the burrow. The animal under observation turned from left to right and back again a number of times, as though exploring the wall of the burrow with the foot, before it made any boring movements. Probably thus in some way *Teredo* becomes aware of the proximity of neighboring burrows, so as to turn aside and avoid them. In executing these turning movements, the foot several times passed directly across the glass, so that the manner in which it functioned could be well studied. The organ was first flattened against the surface of the glass, and its margins spread out so that they extended beyond the edges of the shell. Then, apparently by contraction of the retractor muscles, the margins were rather suddenly drawn in and the central disc of the foot slightly cupped, obviously constituting a sucker. After each contraction the foot sought a new attachment, moving laterally about 0.5 mm. and hitching the shell along to a new position. Thus the turning of the shell was really accomplished by a sort of crawling around the burrow with the foot.

During the course of this exploration of the walls of the burrow, the animal was observed to turn about its long axis 260 degrees in one direction and 220 degrees in the other, or a total of 480 degrees. The viscera were obviously twisted, owing to the animal's being attached to the burrow at the posterior end, but this twisting appeared to occasion it no inconvenience. Thus is solved the problem of how the shell can be brought into the various positions necessary for excavating the regularly cupped, perfectly rounded burrow. It was obvious from the markings shown in figure 85, that the shell must have been rotated by slow stages through at least 180 degrees in each direction in order to produce these striations radiating in all directions.

The possibility has often been suggested that *Teredo* may facilitate its boring by the use of some secretion which has a solvent action on certain constituents of the wood. It would seem that the action of such a substance, if it occurs, should spread at least for a limited distance through the cells of the wood immediately adjacent to the extremity of the burrow. The tracheids of Douglas fir are from 1 to 3 mm. in length, and it is hardly conceivable that a secretion applied to one end of a tracheid should not spread through its entire length. Probing in the extremity of the burrow with a needle, however, did not reveal any area of softened wood, as would be expected on this hypothesis. Staining with hematoxylin, which is a specific stain for cellulose, did not reveal any diminution of the cellulose content of the wood at the end of the burrow. It was further attempted to compare quantitatively the composition of shavings from wood immediately adjacent to burrows of *Teredo* with that of shavings from sound portions of the same timber. An analysis of these samples did not indicate that any substances had been removed by the enzymes of the borers from the wood forming the wall of the burrow.

The evidence strongly indicates that boring is performed entirely by mechanical rasping with the shell on wood that has been to some extent softened and macerated by the presence of water in the burrow.

The Rate of Boring

The efficiency with which the shell of *Teredo* is applied to boring is amply illustrated by the rapidity with which untreated timbers exposed to attack are reduced to mere honeycombed masses of debris. In the case of heavy attack by either *Teredo navalis* or *Bankia setacea*, under conditions obtaining in San Francisco Bay, from five to six months is sufficient time for untreated piling to be entirely destroyed at the mud line.

The average individual rate of boring under a given set of conditions is difficult to determine because of the practical impossibility of knowing accurately the time at which any specimen had entered the wood. As attachment of larvae occurs over a considerable period of time, individuals of varying sizes and ages occur together in the same timber. To include the smaller specimens in the calculations involves the error of the differential time element, while to consider only the largest specimens does not give a fair average. However, on the basis of the latter alternative, some approximation of the rate of boring has been attempted.

The following tables of the rate of growth of *Teredo navalis* and *Bankia setacea* are based on measurements of the largest individuals found in samples of Douglas fir wood exposed for known lengths of time at the localities given. Only the largest specimen occurring in each sample is listed, on the assumption that such specimens are the ones which entered the wood soonest after its exposure, and hence are the ones whose ages are most accurately known. The error in this method of selection lies in the fact that it includes those individuals which not only are the oldest, but which

also have grown most rapidly. This error is to some extent compensated for by the consideration that in estimating the ages of the various individuals measured a considerable margin has been allowed, the "presumed date of attack" being set at the earliest time at which it is believed that larval settlement might have occurred.

A majority of the figures given represent measurements of specimens occurring in test boards immersed for stated periods of time during the breeding season. In such cases the presumed date of attack is arbitrarily set at two weeks after the date of immersion, as it has been observed that test boards of seasoned lumber are rarely or never attacked until after they have been in the water for this length of time. Some of the figures tabulated (those marked with an asterisk) are measurements of specimens occurring in test boards immersed prior to the commencement of the breeding season, or in piling exposed for other than experimental purposes. In these instances the presumed date of attack is set at two weeks prior to the earliest date at which larval settlement is known to have occurred in the year in question. The presumed age is therefore the maximum that is considered at all possible. Even so, the rate of boring

TABLE No. 28

RATE OF BORING OF TEREDO NAVALIS IN SAN FRANCISCO BAY

Locality	Nature of sample	Date immersed	Presumed date of attack	Date removed	Presumed age of specimen	Length in cm.	Average rate of boring (cm. per mo.)
Goat Island.....	1″ x 6″ test board	July 15 1921	Aug. 1	Sept. 15	1½ mos.	1.3	.9
" "	"	Aug. 15	Sept. 1	Oct. 15	1½ mos.	1.0	.7
* " "	"	Mar. 12	Aug. 1	Sept. 15	1½ mos.	2.2	1.5
" "	"	July 15	Aug. 1	Oct. 15	2½ mos.	4.3	1.7
" "	"	Aug. 15	Sept. 1	Nov. 15	2½ mos.	4.0	1.6
" "	"	Sept. 15	Oct. 1	Dec. 19	2½ mos.	(2.6)	(1.0)a
* " "	"	Mar. 12	Aug. 1	Oct. 15	2½ mos.	7.0	2.8
* " "	"	Mar. 12	Aug. 1	Nov. 15	3½ mos.	8.0	2.3
* " "	"	Apr. 15	Aug. 1	Nov. 15	3½ mos.	9.0	2.6
* " "	"	1922 May 15	Aug. 1	Nov. 15	3½ mos.	11.0	3.1
Fort Scott Mine Dock.........	"	Aug. 16 1921	Sept. 1	Jan. 13	3½ mos.	(4.0)	(1.1)b
" "	"	Oct. 18 1921	Nov. 1	Aug. 15 1922	9½ mos.	(6.5)	(.7)c
Oakland Harbor Light.........	"	July 12 1921	Aug. 1	Oct. 15	2½ mos.	6.7	2.7
" "	"	Aug. 15	Sept. 1	Nov. 16	2½ mos.	3.0	1.2
* " "	"	Apr. 12	Aug. 1	Nov. 16	3½ mos.	(20.0)	(5.7)d
* " "	"	June 12	Aug. 1	Nov. 16	3½ mos.	10.6	3.3
* " "	"	May 12	Aug. 1	Dec. 14	4½ mos.	12.0	2.7
*Oakland Mole...	Pile	1918	Aug. (?) 1919	Aug. 3 1921	24 mos.	50.8	2.1
*Crockett.......	1″ x 6″ test board	March 1921	Aug. 8	Nov. 8	3 mos.	10.0	3.3
"	"	March	Aug. 8	Dec. 12	4 mos.	11.0	2.8
*Port Costa......	2″ x 4″ test board	Mar. 14 1922	Sept. 28	Dec. 4 1923	14 mos.	29.2	2.1

TABLE No. 29

SUMMING UP TABLE 28

(*a*, *b*, *c*, and *d* omitted from averages)

Age in months	Number of individuals	Average length in cm.	Average rate of boring over entire period in cm. per month	Average rate of boring since preceding age in cm. per month
1½	3	1.5	1.0	...
2½	5	5.0	2.0	3.5
3½	4	9.7	2.8	4.7
4½	1	12.0	2.7	2.3
14	1	29.2	2.1	1.8
24	1	50.8	2.1	2.2

of the specimens indicated by the asterisk is generally higher than that of the others, which would suggest that in wood which has been immersed long enough to become well water-soaked boring proceeds more rapidly than in test boards only recently immersed.

It appears from the foregoing tabulation of data that the normal rate of growth of *Teredo navalis* under favorable conditions in San Francisco Bay is 1.5 cm. during the first 1½ months (1.0 cm. a month), increasing to 3.5 cm. the following month, and reaching a maximum of 4.7 cm. (1⅞ inches) during the period elapsing between 2½ and 3½ months. After this the rate of boring declines, averaging 2.3 cm. between 3½ and 4½ months, and 1.8 cm. a month over the period between 4½ and 14 months. This decline in rate of growth during the fourth month and subsequently may represent a function of the normal growth cycle, or the effect of the lower temperatures of winter, or both. It will be noted that during the periods September-January, October-December and November-August (*a*, *b* and *c* in Table 28), the rate of growth is considerably less than during the warmer months of the year.

The average rate of growth per month between 14 and 24 months, in the one individual considered, is 2.2 cm. per month. This slight increase over the average rate between 4½ and 14 months is not considered significant. It would appear that the normal rate of boring over a period of months is in the neighborhood of 2 cm. (¾ inch) per month.

The individual which reached a length of 50.8 cm. (20 inches) is the largest specimen of *Teredo navalis* that has been found in the course of this investigation.

The results tabulated in tables 30 and 31, although more erratic than those found in the case of *Teredo navalis*, show a much more rapid growth for *Bankia setacea*. They indicate that during the first 1½ months the growth approximates 3.5 cm. (2.3 cm. a month). During the following month the rate of growth increases slightly, being 3.0 cm. Between 2½ and 3½ months the rate of growth leaps suddenly to 11.1 cm. As only one specimen of an age of 2½ months was available for measurement, it is likely that the apparent rate of growth between 1½ and 2½ months is too low, and that between 2½ and 3½ months correspondingly too high. But it is obvious that here, as in the case of *Teredo navalis*, the maximum rate of growth occurs during the period between 2½ and 3½ months. The decline which follows cannot in this case be attributed to low temperatures. The breeding season of *Bankia* is several months earlier than that of *Teredo*, so that this decline in rate of growth occurs about midsummer.

TABLE No. 30

RATE OF BORING OF BANKIA SETACEA IN SAN FRANCISCO BAY

Locality	Nature of sample	Date immersed	Presumed date of attack	Date removed	Presumed age of specimen	Length in cm.	Average rate of boring (cm. per mo.)
Goat Island......	1″ x 6″ test board	Mar. 12 1921	Mar. 28	May 14	1½ mos.	3.7	2.5
" "	"	July 15	Aug. 1	Sept. 15	1½ mos.	3.2	2.1
" "	"	Feb. 15	Mar. 1	May 15	2½ mos.	6.5	3.0
" "	"	Mar. 12	Apr. 1	July 15	3½ mos.	19.7	5.6
" "	"	Apr. 12	May 1	Aug. 15	3½ mos.	27.0	7.7
" "	"	May 15	June 1	Sept. 15	3½ mos.	16.0	4.6
" "	"	June 15	July 1	Oct. 15	3½ mos.	19.0	5.4
" "	"	Apr. 15	May 1	Oct. 15	5½ mos.	20.0	3.6
" "	"	Mar. 15	Apr. 1	Oct. 15	6½ mos.	21.0	3.2
Fort Scott Mine Dock.........	"	Mar. 15	Apr. 1	July 21	3¾ mos.	12.0	3.2
" "	"	Apr. 25	May 9	Aug. 28	3¾ mos.	12.0	3.2
" "	"	May 14	June 1	Oct. 18	4½ mos.	15.0	3.3
" "	"	May 14	June 1	Dec. 15	6½ mos.	34.0	5.2
*China Basin.... S. F.	Pile	Feb. (?) 1922	Mar. 1	Aug. 18	5½ mos.	32.0	5.8
*Oakland........ S. P. Mole	"	May 22 1923	June 5	Oct. 22	4½ mos.	28.0	6.2
" "	1″ x 6″ test board	Jan. 21	Feb. 4	Oct. 6	8 mos.	50.0	6.3

TABLE No. 31

SUMMING UP TABLE 30

Age in months	Number of individuals	Average length in cm.	Average rate of boring over entire period in cm. per month	Average rate of boring since preceding age in cm. per month
1½	2	3.5	2.3	...
2½	1	6.5	3.0	3.0
3½	6	17.6	5.0	11.1
4½	2	21.5	4.7	4.0
5½	2	26.0	4.7	4.5
6½	2	27.5	4.2	1.5
8	1	50.0	6.3	...

It appears that each species has an optimum temperature for reproduction, settlement of larvae and growth, which in the case of *Bankia setacea* occurs in the late winter and early spring, and in the case of *Teredo navalis* occurs in late summer and early fall. Thus it is conceivable that the higher temperatures of summer might prove as unfavorable to the growth of *Bankia* as the low temperatures of winter are to *Teredo*.

The last specimen listed in tables 30 and 31 is interesting as indicating the possi-

bilities of growth under favorable conditions. This specimen is presumed to have been 8 months old, and could not possibly have been more than $8\frac{1}{2}$ months old, as the board in which it occurred was immersed only for that period of time. Yet it had attained a length of 50 cm., having thus grown at an average rate of 6.3 cm. ($2\frac{1}{2}$ inches) a month over the entire period. In general, however, the rate of growth of this species over a period of months appears to approximate 4.7 cm. ($1\frac{7}{8}$ inches) a month.

All of the above data refer to the rate of boring in Douglas fir timber. In harder woods the boring proceeds more slowly, as it does also in salinities that are much below the optimum for the organisms.

It has been frequently observed that, in the case of untreated piles standing side by side, the softer, more open-grained piles are much more rapidly and thoroughly destroyed by the burrows of *Teredo* than tough, close-grained piles. A specimen of greenheart timber submerged at the Oakland Mole, January 5, 1923, was found to contain a few specimens of *Teredo navalis* of a maximum length of 1.9 cm. on May 27, 1924. As these organisms must have settled on the wood not later than December, 1923, this represents the boring accomplished in 5 months or more. It has been observed also that boring proceeds more slowly in eucalyptus piling than in fir.

In localities in Suisun Bay, especially above Martinez, where *Teredo* is subjected to conditions of much stress owing to the low and constantly fluctuating salinities, the rate of growth of the organisms and the consequent destruction of timber are much reduced as compared with localities farther down the bay.

The rate of destruction of timber by the burrows of *Teredo* or *Bankia* is a function of the individual rate of boring and the density of the attack. These are, within certain limits, variables with relation to one another, as growth is retarded by crowding. In general, however, the destruction of timber is more rapid and complete when penetrated by numerous small, crowded specimens than when penetrated by fewer, although larger, more rapidly boring individuals. For this reason the work of *Bankia*, the larger and less prolific organism, is ordinarily not so immediately and phenomenally destructive as that of *Teredo*, which is smaller, but settles on timber in much greater numbers.

A striking illustration of the possibilities of destruction of timber by *Teredo navalis* is afforded by certain experimental timbers placed at Port Costa in 1920 by the Southern Pacific Company. Rough and planed timbers of Douglas fir, 6 by 8 inches, were placed in 18 feet of water at the Port Costa wharf on April 2 and May 5, 1920. These were found on August 4 to be lightly infected (in salinities averaging about 20 parts per 1000). On August 16 the infection was heavy, averaging 130 minute teredos per square inch of surface near the mud line. The pits had a diameter of 0.008 inch, and were only deep enough to accommodate the minute shell of the young borer. On August 26 the opening had increased to 0.01 inch and its depth to 3/32 inch, while its diameter below the surface increased abruptly to 1/16 inch. The salinity during this period had reached 25 parts per 1000.

On September 15 another examination was made in salinities of 28 parts per 1000. The orifices of the burrows had enlarged to 0.013 inch, and growth had been rapid. A few of the larger borers had attained a length of 1.3 to 1.8 inches, but the great majority were only 0.40 to 0.65 inch. The settlement of larvae and the growth of the borers continued rapidly, especially near the mud line, into October, when larval settlement declined. On September 25 the penetration was 1.5 inches. The highest salinity of the year, 29 parts per 1000, was recorded at this time.

On December 8 these timbers were examined, and also some others planted

July 1. All were found to be heavily infected and several broke under their own weight at or near the level of the mud line when lifted up on the wharf (fig. 87).

Sections of a timber planted July 1 (fig. 88) show that the 6 by 8 inch timber had been completely riddled at the mud line by *Teredo*. This timber had been examined on August 4 and showed no infection at that time. Thus in 4 months, or at the most 126 days, this timber was utterly destroyed at the mud line. A similar

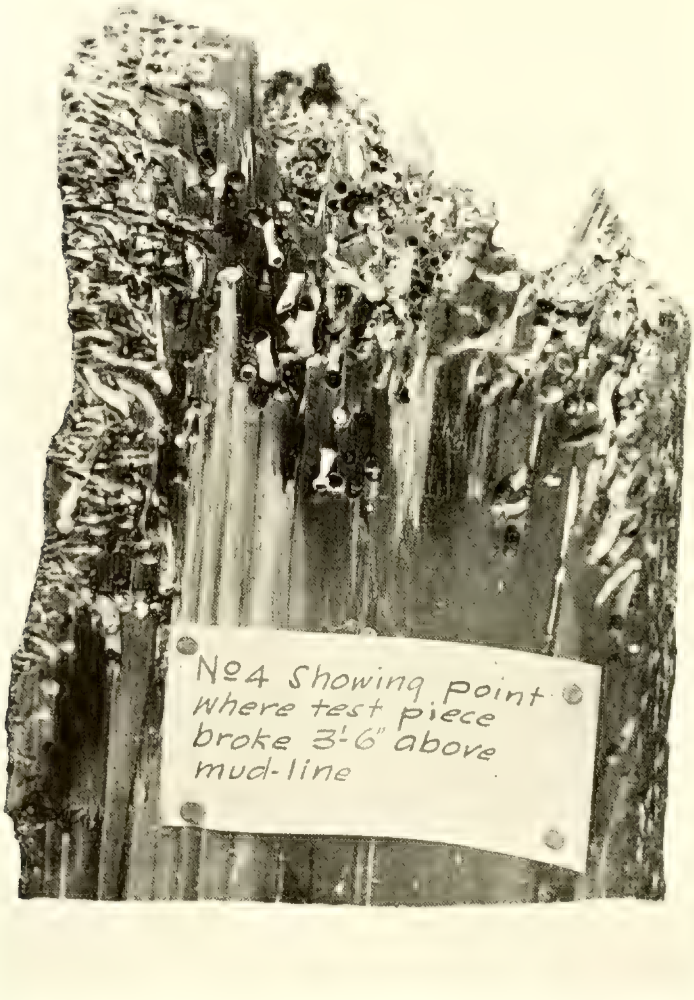

Fig. 87. Breaking point of a 6 x 8 Douglas fir timber planted at Southern Pacific wharf, Port Costa, California, July 1, 1920. First larvae detected at this locality on August 4. Timber removed December 8, 1920. Destroyed by *Teredo navalis*.

attack on a 12-inch pile would penetrate three-fourths of its cross section and reduce its efficiency below the danger line.

The rate of destruction of timber by *Bankia setacea* is generally slower than in the case of *Teredo navalis*. Its larger, more rapidly driven burrows occur typically more sparsely than the burrows of *Teredo*, and the substance of the wood is not so thoroughly destroyed. Piling in dolphins of the Alameda Mole, driven in February,

1919, at just the proper season to be attacked by *Bankia*, gave service until November, 1920, when they were so weakened that it was found necessary to remove them. Thus they lasted for about 20 months. An untreated pile driven in the Northwestern Pacific wharf at Tiburon in 1919 was not entirely destroyed when examined on December 14, 1921, although exposed to the combined attack of *Bankia* and *Limnoria*, and some *Teredo*, during the intervening two years.

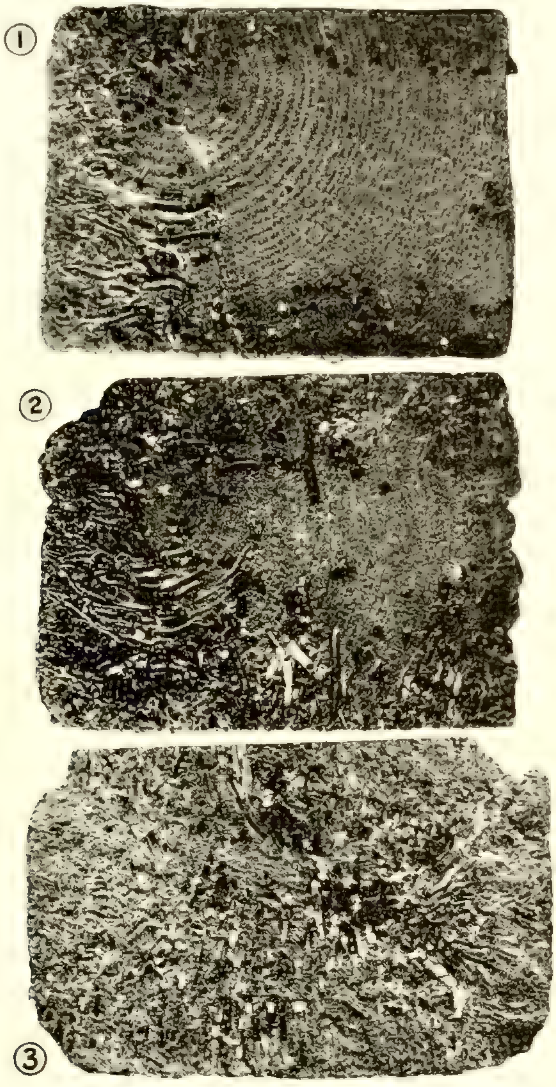

Fig. 88. Cross-sections of a companion timber to that shown in figure 87; exposed during the same period.
(1) Section 10 feet, 2 inches above mud line.
(2) Section 6 feet, 6 inches above mud line.
(3) Section 6 inches above mud line.
Note contrast between inshore (right) and offshore (left) sides in the intensity of attack and destruction.

On the other hand, attack by *Bankia* at its worst can hardly be exceeded by the worst instances of damage by *Teredo*. Untreated Douglas fir piling driven in the false work of the new China Basin Warehouse in San Francisco, in February, 1922, was thoroughly riddled at the mud line by *Bankia* when examined on August 18. An in-

stance of even more rapid destruction is furnished by piling driven in a pipe line to a dredge near the Southern Pacific Oakland Mole on or about May 22, 1923, and removed October 22. Some of these piles were entirely destroyed at the mud line by *Bankia*, as illustrated in figs. 89 and 90. This destruction had accordingly occurred in 5 months or possibly less. The piling, being already watersoaked, was doubtless attacked soon after the driving.

The Wood Used as Food

The question whether or not *Teredo* derives any nourishment from the wood in which it bores has been almost as much debated as the problem of the method of boring. As has been previously stated, the particles of bored wood are normally

Fig. 89. Breaking point, near mud line, of pile at Oakland Mole, destroyed within 5 months by *Bankia setacea*.

swallowed, and later extruded from the burrow through the anal siphon, after passage through the digestive tract. The fact that the caecum is always found filled with the borings is of itself no proof that they are in process of digestion. The caecum might conceivably be merely a reservoir for temporary storage of the particles, in order to keep them separated from the plankton food. The presence of the well developed typhlosole throughout the length of the caecum, however, and the fact that this typhlosole is supplied with blood from a large artery direct from the heart, afford considerable evidence that nutritive substances are removed from the wood during its temporary lodgment in the caecum. On *a priori* grounds, also, it would be surprising if *Teredo* were entirely to neglect so proximate a source of food as is afforded by the wood particles passing through its digestive tract.

Nevertheless, it has been somewhat generally assumed that the wood particles are merely mechanically handled by the borers and extruded from the burrow chemi-

cally unchanged, being passed through the digestive tract simply because there is no other convenient method of disposing of them. Certain near relatives of *Teredo* (*Pholas*, *Zirfaea* and *Saxicava*) bore in such substances as sandstone, limestone, shale, marl and gneiss—materials which cannot be supposed to yield them any nourishment; yet these indigestible borings may be found in considerable quantities in the digestive tract of the rock borers. The principal constituents of wood, cellulose and lignin, are notably resistant to digestive action, so that they pass through the digestive tract of many animals entirely unchanged by the enzymes there encountered. Further, wood that has passed through the digestive tract of *Teredo* is shown by microscopic study to have retained its cellular structure, as seen in fig. 91, and some investigators claim to have identified the kind of wood by its odor and color. On the basis of these considerations, the statement has been commonly made that *Teredo* derives no nutriment

Fig. 90. Split section of pile shown in fig. 89.

from the wood, but subsists, as do other lamellibranchs, on a diet of plankton organisms filtered from the water which is continually passing in and out through the siphons.

Recently this problem has been approached from the biochemical point of view, and rather definite conclusions have been arrived at. Harington (1921), working at the Plymouth Laboratory, has shown that a certain enzyme or enzymes extracted from the excised livers of *Teredo norvegica* will act on sawdust to produce glucose, a substance which is readily absorbed into the blood and consumed in the tissues of animal organisms. His results are not as conclusive as might be desired, since the liver extract failed to reduce pure cellulose in his experiments. It is possible that the action on the sawdust was limited to the small amounts of hemicelluloses present, which are much more easily broken down than is pure cellulose.

The problem was then attacked from another angle by Dore and Miller (1923), in connection with the investigations of this Committee. It was undertaken to determine whether or not the wood particles are chemically changed in their passage through the digestive tract, by analyzing and comparing the composition of the ejected borings with that of the original wood. Blocks of wood containing numerous teredos were kept in aquaria, where the organisms continued boring and appeared to thrive. From time to time the wood borings ejected from the siphons were removed from the aquaria with a long pipette. In about eight months sufficient material was accumulated by this method to permit of successful analysis.

The possibility was recognized of changes occurring in the composition of the wood subsequent to ejection, especially as it was not always possible to collect the borings with desirable promptness. In order to test the probability of such changes, some of the borings (series 1, sample 2, below) were allowed to remain on the bottom of the aquarium for about six months before being pipetted off.

Fig. 91. Wood borings ejected by *Teredo*, x 300. Observe that in many of the particles the cell walls are visible.

The borings as collected were dried overnight at 100 degrees C. in an electric oven, and the dried mass then crushed to pass a wire sieve having 50 meshes to the linear inch. Samples of the original wood were reduced to sawdust, then ground to pass through the 50-mesh sieve.

In tables 32 and 33 below are given the results of analysis of wood and borings from two different aquaria.

The purpose in determining moisture, ash and protein was to enable all the data to be reduced to a comparable basis. Since normal wood contains but small amounts of ash and protein, the amounts found of these constituents may be taken as an approximate measure of the non-woody substances present in the samples. Accord-

ingly, ash represents chiefly mineral contamination (shell fragments, salt, etc.), while protein represents animal remains.

TABLE No. 32

ANALYSES OF WOOD AND BORINGS. SERIES I.

As found. All figures in percentages of air-dried material.

Determination	Original Wood			Borings, Sample 1			Borings, Sample 2		
	Individual		Average	Individual		Average	Individual		Average
Moisture	4.89	4.91	4.90	7.36	....	7.36	7.31	....	7.31
Ash	8.42	8.02	8.22	24.17	....	24.17	30.66	....	30.66
Calcium in ash	0.62	0.68	0.65	0.66	....	0.66	....	....	....
Nitrogen	0.08	0.08	0.08	0.38	....	0.38	0.74	....	0.74
Protein (N x 6.25)			0.50			2.27			4.62
Benzene extract	0.37 0.37	0.38 0.35	0.37	0.36 0.34	0.25	0.32	0.48	0.39	0.44
Alcohol extract	7.96 8.00	7.90 7.13	7.75	27.09 27.03	25.60	26.57*	......		
Sugars in alcohol extract	0.33 0.44	0.32 0.32	0.35	0.09	0.15	0.12	....		
Hemicelluloses (as dextrose)	4.21** 5.04	5.32 5.24	5.20	4.24	4.32	4.28	5.08	5.64	5.36
Cellulose	47.08	47.52	47.30	14.79	13.04	13.91	11.54	....	11.54
Lignin	26.47	26.41	26.44	36.11	....	36.11	32.13	....	32.13
Furfural yield	4.75	4.53	4.64	3.91	....	3.91	3.38	....	3.38

*Contains much NaCl. **Excluded from average.

TABLE No. 33

ANALYSES OF WOOD AND BORINGS. SERIES II.

As found. All figures in percentages of air-dried material.

Determination	Original Wood			Borings		
	Individual		Average	Individual		Average
Moisture	8.47	8.65	8.56	7.49	7.15	7.32
Ash	6.90	7.08	6.99	18.83	18.87	18.85
Nitrogen	0.14	....	0.14	0.70	0.72	0.71
Protein (N x 6.25)	0.87	....	0.87	4.38	4.50	4.44
Benzene extract	0.46 0.39	0.39 0.36	0.40	0.40 0.38	0.42 0.47	0.42
Sugars in alcohol extract	nil	nil	nil	nil	nil	nil
Hemicelluloses (as dextrose)	11.08 11.76	12.64 12.08	11.87	8.44	8.48	8.46
Cellulose	39.44	39.87	39.66	14.12	15.79	14.95
Lignin	23.63	22.91	23.27	38.16	37.71	37.93
Furfural yield	4.93	....	4.93	5.80	....	5.80

The analytical figures for the respective wood samples and their corresponding borings are not directly comparable with one another, since they are mixed with different amounts of non-woody material. In order to bring them to a common basis, the data have been recalculated to a moisture-free, ash-free and protein-free basis. The results are given in table 34.

The figures for benzene extract and alcohol extract appear to have no special significance. The former represent resinous matter, the latter tannins, coloring matter, and soluble sugars. None of these except the soluble sugars can be regarded as having any nutritive value for animals. The analyses show that extremely small amounts of soluble sugars are present even in the original wood. Accordingly, neither benzene soluble nor alcohol soluble constituents have been considered in the recalculations.

TABLE No. 34

RECALCULATIONS OF DATA OF TABLES 32 AND 33

	Series I			Series II	
	Wood	Borings (1)	Borings (2)	Wood	Borings
Moisture—plus ash, plus protein...	13.62	33.80	42.59	16.42	30.61
Moisture-free, ash-free and protein-free material....................	86.38	66.20	57.41	83.58	69.39
DATA RECALCULATED TO MOISTURE-FREE, ASH-FREE, AND PROTEIN-FREE BASIS					
Hemicelluloses....................	6.02	6.46	9.33	14.23	12.19
Cellulose..........................	54.74	21.01	20.10	47.45	21.54
Lignin..............................	30.60	54.55	55.97	27.84	54.66
Furfural yield......................	5.37	5.91	5.89	5.90	8.36

The data show that each of the samples of ejected wood contains a much lower percentage of cellulose and a much higher percentage of lignin than the wood from which it was derived. The figures for hemicelluloses and furfural yield are less regular and not readily comparable on the basis given.

Inasmuch as it is extremely unlikely that any lignin was synthesized during the passage of material through the digestive tract of the animal, the increase in lignin is to be ascribed to concentration by removal of cellulose and other wood constituents. Assuming that the absolute amount of lignin remaining in the residue is the same as was in the original wood, we may calculate the percentage of the original wood substances remaining in each of the three samples of borings by determining in each case the ratio of the lignin content to that of the original wood. Thus the percentages of original wood substances in samples of borings are:

$$\text{Series 1, sample 1} \ldots\ldots\ \frac{30.60}{54.55} \times 100\% = 56.1\%$$

$$\text{Series 1, sample 2} \ldots\ldots\ \frac{30.60}{55.97} \times 100\% = 54.7\%$$

$$\text{Series II} \ldots\ldots\ldots\ldots\ \frac{27.84}{54.66} \times 100\% = 50.9\%$$

The data of table 34 have been recalculated so that the constituents of the borings are expressed, not on 100 parts of borings, but on 100 parts of original wood, or in other words, upon the number of parts of borings corresponding to the percentages found in the preceding paragraph. The results are given in table 35.

On this basis it appears that during its passage through the animal's digestive tract the wood has lost about 80 per cent of its cellulose, and from 15 to 56 per cent of its hemicelluloses, including from 11 to 40 per cent of its furfural yielding constituents, such as pentosans, etc.

The simplest explanation of this disappearance of carbohydrate material is that the cellulose and hemicelluloses of wood are partly digested by the teredo and probably hydrolyzed to simple carbohydrates which the animal can use as food.

The cellulose content and lignin content of the three samples of borings are remarkably uniform (see table 34). This would seem to indicate the composition of the residue which the teredo is incapable of digesting.

TABLE No. 35

DATA OF TABLE 34 CALCULATED TO PERCENTAGES OF ORIGINAL WOOD

Determination	Series I			Series II	
	Wood Parts per 100	Borings (1) Parts per 56.1	Borings (2) Parts per 54.7	Wood Parts per 100	Borings Parts per 50.9
Hemicelluloses	6.02	3.62	5.10	14.23	6.20
Cellulose	54.74	11.79	10.99	47.45	10.96
Lignin	30.60	30.60	30.60	27.84	27.84
Furfural yield	5.37	3.32	3.22	5.90	4.26

Reference has previously been made to the possibility that the change in the composition of the wood may occur after the material is ejected by the borer. The compositions of the first and second samples of borings in Series I furnish some experimental evidence on this point. Although the second sample was purposely left in the sea water for at least six months longer than the first, there was no significant reduction in carbohydrate constituents (see Table 34). In view of the extreme resistance of wood to purely chemical action, and the absence of known cellulose-destroying fungi or bacteria in sea water, it seems more reasonable to ascribe the loss of cellulose and other carbohydrates to digestive action while in the body than to external agencies.

Further evidence of the digestion of cellulose was found in the serial sections that were prepared in the course of the investigations of the morphology of *Teredo*. The contents of the stomach, caecum and intestine, usually remained in place in the sections, as shown in the photomicrographs in fig. 79. When sections were stained with Delafield's haemotoxylin, which is a selective stain for cellulose, the wood fibers in the stomach and in the caecum took the stain, while those in the intestine did not to any appreciable degree. Thus it is evident that at least a part of the cellulose had been removed from the wood fibers during their stay in the stomach and caecum. Unfortunately, the difference in color does not show in the photomicrographs. Recent work by Miller and Boynton (1926) has shown that *Bankia setacea* is also capable of utilizing wood as food, wood removed from the caecum having been found to contain about four times as much of reducing sugars as the original undigested wood.

Considerable evidence has been advanced by Potts (1923) to show that the digestion of wood by *Teredo* takes place intracellularly, in certain lobules of the liver. As has been stated above, the livers of *Teredo* are histologically differentiated into two distinct types of lobules, one type (dorsal) being made up of relatively large, close-set, columnar cells, while the ventral lobules consist of smaller, somewhat flattened cells surrounding large lumina. It was observed by Sigerfoos (1908) that these lumina are characteristically filled with particles of wood. According to the observation of Potts, the wood particles taken into the lumina are there seized upon and ingested by free-moving amoeboid cells, within which the wood is presumably digested and prepared for absorption by the animal. Some of the epithelial cells of the liver are also said to contain wood fragments, and it is probable that the free amoeboid cells in the lumen are derived from this epithelium.

This matter has been further studied by Yonge (1926b), who concludes that digestion is probably largely intracellular in most, if not all, the lamellibranchs (*Teredo norvegica* was one of the forms specially investigated). The so-called livers he finds to be not secretory in function, but organs of absorption and intracellular digestion. Amoebocytes, which are found in the lumen of the gut and in and beneath the epi-

thelium also ingest food particles. The only free enzymes in the lumen seem to be the amylolytic ones set free by the dissolution of the crystalline style. Potts (*loc. cit.*) asserts that the stomach, caecum and lumina of the livers contain no other recognizable organic material except wood, and that only very occasional diatoms are found in the intestine. He concludes that *Teredo* subsists for the most part on wood alone, being almost or quite independent of plankton organisms.

The species on which Potts worked are not stated, although he studied several and came to the conclusion that his observations are applicable to the Teredinidae as a group. This seems probable as regards the partial digestion of wood in the liver lobules in the manner described, as the presence of wood particles in the lumina has been observed by Sigerfoos in *Bankia gouldi* and by us in *Teredo navalis*, as well as by Potts and Yonge in the species investigated by them. But regarding the conclusion as to the non-utilization of plankton there is considerable room for doubt.

It does not appear probable that *Teredo* could subsist over any long period upon the wood alone, because of the negligibly small amount of protein material present. For the processes of growth and repair, considerable nitrogenous matter would be required. The need for a simultaneous supply of plankton is accordingly indicated.

While it is true, as stated by Potts, that diatoms compose a relatively small proportion of the contents of the digestive tract, their presence is not to be regarded as negligible. In specimens examined by us the stomach has contained only scattered fragments of wood. The implication is that none of the material ingested is kept for more than a brief time in the stomach, being rapidly passed on to other portions of the digestive tract. In the liver lumen and in the caecum so few diatoms are found that their presence may be regarded as accidental. But the intestine usually

Fig. 92. Section through intestine of *Teredo navalis*, showing a number of diatoms mixed with the wood particles.

contains a number of diatom remains (see fig. 92). Careful computations have shown that as much as 11 per cent by volume of the contents of the intestine may consist of diatoms and other forms which leave skeletal remains. This is too large a proportion of such material to favor the assumption that it has been accidentally ingested along with the particles of wood. Also, the presence of these skeletal remains in the intestine would indicate the ingestion of a proportional number of flagellates and ciliates and other forms which after digestion would not leave any recognizable remains.

The constant passage of the plankton-laden respiratory currents through the mantle cavity, the presence of quantities of plankton in the gill lamellae, the ciliated branchial groove leading forward to the mouth, and the presence of at least rudimentary labial palps all indicate a partial utilization of plankton as food. The teredo which is boring, and consequently growing to fill the larger cavity, requires proteins to provide for growth and repair, and carbohydrates to furnish the energy required for the boring operation. This energy could indeed be supplied from the protein material of the plankton, but much more efficiently by carbohydrates, inasmuch as these last are completely oxidized and there is therefore no necessity of getting rid of nitrogenous products. If, then, when its boring activities are greatest, the teredo has available a considerable supply of carbohydrate material to furnish the necessary energy, and that available in proportion to the amount of work being done, it appears to be a natural arrangement, admirably adapted to its needs. The carbohydrates of the wood therefore play an important part in supplying the teredo with energy when it is most needed.

If the conclusion be accepted that the wood is partly digested and absorbed as food by *Teredo*, some light is thrown upon the probable mechanism by which toxic substances injected into the timbers of marine structures protect against teredo attack. If partial digestion of wood occurs, it is clear that all substances contained in the wood must be subjected to an intimate contact with the animal's digestive fluids over a considerable period of time. Optimum conditions then prevail for the absorption of toxic substances, and their effectiveness is limited only by such factors as lack of solubility, inability of their solutions to penetrate the walls of the digestive tract, etc., these factors being dependent upon the properties of the agent and not on the conditions of exposure. No case of failure of a given toxin can be ascribed to physical isolation of the borings as we might expect if the wood were regarded as wholly undigested and merely mechanically handled by the teredo.

These considerations offer practical suggestions in regard to (1) the commercial preservative treatment of marine timbers, and (2) the testing of the toxicity of supposed preservative substances. We may conclude that the established practice of preserving marine timbers by impregnating the wood with toxic substances is a rational and efficient process for introducing these substances into the animal's system, for it is clear that the teredo cannot bore into the wood without being exposed to the action of any toxins that are capable of entering its system through the digestive tract. As to methods of carrying out toxicity tests, it would appear that those methods which use the wood as a vehicle for carrying the toxin possess a distinct advantage over methods in which the toxin is introduced into the animal by some other means.

The practice followed by this Committee of testing various preservatives by immersing in the Bay for considerable periods of time samples of timber treated with the preservatives in question accordingly affords a much better basis for sound conclusions as to the usefulness of these treatments than would the alternative of direct toxicity experiments in the laboratory.

CHAPTER XVI

THE BIOLOGY OF TEREDO NAVALIS

In undertaking an investigation of the biology of a group of organisms, it is usually most feasible to select a single species as a type for a thoroughgoing study, and to consider the others by comparison with it, rather than to attempt what in the nature of the case would be a more or less superficial investigation of the group as a whole. In the present case, accordingly, *Teredo navalis* has been selected as a type for particular study, this in view of its widespread distribution, its unusual adaptability to the conditions of new environments, its extraordinary capacity for speedy and complete destruction of timbers exposed to its ravages, and especially its recent unprecedented depredations in San Francisco Bay.

In the following pages are presented a somewhat detailed account of the biology of this organism, the history of its introduction to and subsequent behavior in San Francisco Bay, and its relation to physical factors of the environment, especially with regard to the conditions which are favorable or otherwise to its growth and reproduction, and the invasion of previously uninfected localities.

The record of *Teredo navalis*, since our earliest knowledge regarding it, has been a history of sudden and usually calamitous, because unexpected, invasions. It is therefore a matter of the highest importance to analyze the conditions which permit such recurring outbreaks, in order that they may be anticipated in future, here and elsewhere, and steps be taken to avoid a repetition of such disasters as that which has afforded the occasion of this investigation.

THE HISTORY OF TEREDO NAVALIS IN SAN FRANCISCO BAY

At the entrance to Mare Island Strait, at the northern extremity of San Pablo Bay, three long dykes of wooden piling were erected about 1905. The purpose of these dykes was to direct the tidal currents in such a way that the channel should not become filled with silt. Untreated piling was used in the construction of the dykes, as in marine construction generally in this portion of San Francisco Bay. Shipworms had not been known to occur at all in the upper reaches of the bay, and it was confidently believed that the lowered salinities which prevailed as a result of the inflow of fresh water from the San Joaquin and Sacramento rivers constituted an effectual deterrent to these organisms. Consequently it was a matter of considerable surprise when, in January, 1914, an inspection of the Mare Island dykes showed extensive damage by shipworms.

In the spring of the same year damage by these organisms was also noticed in the piling of a wharf on the opposite side of the bay, a half mile below Crockett, and about the same time it was discovered that piling in the dock of the Union Oil Company at Oleum had been similarly attacked. It is probable that shipworms would have been found in the piling of other docks in this neighborhood at this time if a search for them had been made; but the damage was not sufficiently serious to attract general attention. Barrows (1917) states that in this first attack much of the brace piling of the dykes was more than half eaten through, but the sheet piling, which was somewhat less exposed, was not so heavily attacked.

The organism occasioning this damage was at first believed, on the basis of an identification by Dr. Paul Bartsch of the U. S. National Museum, to be *Teredo diegensis*, but was subsequently found to be identical with the *Teredo navalis* of European waters.

The problems of how and when this organism was introduced to San Francisco Bay must doubtless always remain unsolved. It was not found here in an investigation of shipworms made for the United States Forest Service by Kofoid and Armstrong in 1910-1911, nor was it brought to light in the biological survey of San Francisco Bay in 1912-1913 by the United States Bureau of Fisheries and the University of California. Barrows (1917) considers that the first infection probably occurred in the summer of 1913, during a period of increased salinity in San Pablo Bay following a season of unusually scant rainfall and consequently of lessened river discharge. The persistence of such conditions the following year afforded an unusual opportunity for the organism to become established in this locality and to spread to other portions of the bay. The damage at this time, however, was not sufficiently serious to attract general attention, and apparently abated the following year in consequence of a season of more than normal rainfall and river discharge.

A repetition of the damage by *Teredo* was noticed in January, 1917, on the outermost dyke at Mare Island. This was during a period of reduced river discharge, following three years in which it had been more than normal. The maximum penetration was about three inches, and the damage was not as serious as in 1913-1914. By this time, however, the organism had apparently gained a thorough foothold in the region, and conditions grew rapidly worse, shortly assuming the proportions of a commercial catastrophe.

In October, 1919, a dock at Oleum collapsed (see fig. 1), precipitating several loaded freight cars into the bay. In December of this year it was found that the piling of the Southern Pacific slips at Port Costa and Benicia had been penetrated by *Teredo* to a depth of two or three inches, and in some cases the piles were almost completely eaten through at the mud line. During this season the range of the borers was extended upstream into Suisun Bay, at least as far as Martinez, where they were found to have penetrated the piling of the wharf of the Mountain Copper Company one-half inch by March, 1920. At this wharf, and probably at Port Costa and Benicia, the borers were exterminated by the flood waters of April and May, 1920. But the following summer and autumn were again favorable to the propagation and spread of *Teredo*, and the record of this season is one of disaster unprecedented in the history of the ravages wrought by marine borers.

By the autumn of 1920 the borers had spread upstream until they reached Antioch on the San Joaquin River, 25 miles above Carquinez Strait. In the upper bay, from Pinole, through Oleum, Mare Island, Vallejo, Crockett, Port Costa, Benicia and Martinez, to Avon, the destruction of piling by *Teredo* during this season reached a climax which left little or no untreated piling intact, and much of it completely destroyed by penetration to or near the center at the mud line. The nature and degree of the damage at some of these localities is strikingly shown in figure 1.

Above Martinez the attack was widespread, but owing to the adverse effect of lower salinities the growth of the borers was slower, and the penetration of piling was not sufficiently rapid or deep to attain the level of a commercial catastrophe.

This progressive invasion was the direct result of a shortage of rainfall and run-off during three years preceding the summer of 1920, which conduced to the settling of the larvae on unprotected piling during the breeding season of the summer and fall, and the survival of the borers in the wood during the brief seasons of the spring freshets of those years.

In the meantime the invasion by *Teredo navalis* had spread elsewhere to unprotected structures, such as those above Black Point on Petaluma Creek, to the wharves

at Richmond, to the unprotected piling of the dolphins at the Alameda Mole, to some points in the Oakland Estuary, to Bay Farm Island Bridge and to the Dumbarton Bridge at the southern end of the bay. It was also found in 1920 at South San Francisco, in the Bay View sewer outlet and at the sewer outlet at Hunter's Point, in new piling in the boom at Islais Creek, and sparingly at Pier 7 on the San Francisco waterfront, in treated piling which had been opened up by *Limnoria* attack. Since that time it has been found at Fort Point, at Tiburon, at Goat Island, at the Oakland Mole—in short, at practically every locality in San Francisco Bay where untreated piling has been available for examination, or where test boards have been exposed for experimental infection.

While the most spectacular damage by this organism has occurred in the brackish waters of San Pablo and Suisun Bays, this is probably due primarily to the presence there of a large amount of untreated piling rather than to a predilection of the borer for the less saline waters of that region. Very heavy infection of test boards by it have occurred at some stations in San Francisco Bay proper, notably at Goat Island and at Dumbarton. Its sparse occurrence along the San Francisco waterfront and at Fort Point is probably due in part at least to the absence of neighboring foci of infection. But the optimum salinity for *Teredo navalis* is doubtless less than that of normal sea water. It has generally been considered an organism more particularly of the brackish water environment, and as a pest its activities have been particularly noticeable in those regions which, on account of lowered salinities, are immune from most other boring organisms.

PHYSICAL FACTORS INFLUENCING NUMBERS AND DISTRIBUTION

Among the physical factors of the environment which may be presumed to exercise an influence on the growth and reproduction of *Teredo* are salinity, temperature, turbidity, dissolved gases and hydrogen-ion concentration. All of these factors have received consideration in the present investigation, with the result that the first two have been found to be emphatically the most important.

An analysis of these conditions as prevailing in San Francisco Bay, and their observed effect on *Teredo navalis* will be presented in the following pages.

Physical Conditions in San Francisco Bay

San Francisco Bay exhibits a series of conditions of peculiar interest from an ecological point of view. As regards salinity, depth, and temperature, and somewhat, as well, the contour of the shores, the bay naturally divides itself into three major portions, which we may term according to geographical position "upper," "middle," and "lower." The upper bay includes San Pablo and Suisun Bays and the connecting strait (see map, frontispiece), being bounded on the south by a line from Point San Pedro to Point San Pablo. The middle bay extends from this line southward to "a line through the (San Francisco) Ferry Building and Goat Island Light" (Sumner, et al., 1914, p. 22). The lower bay includes the remaining portion south of this line.

These three divisions, taken as a whole, manifest three rather distinct sets of ecological conditions.

The upper bay represents the brackish water environment, with continually fluctuating salinity and maximum range of temperature throughout the year. Receiving at its upper end the combined discharge of the Sacramento and San Joaquin rivers, this segment of the bay is very greatly affected by the inflow of so considerable a quantity of fresh water. The interaction of run-off and tidal movement produces a daily and almost hourly change in salinity, which is altered further by variations in

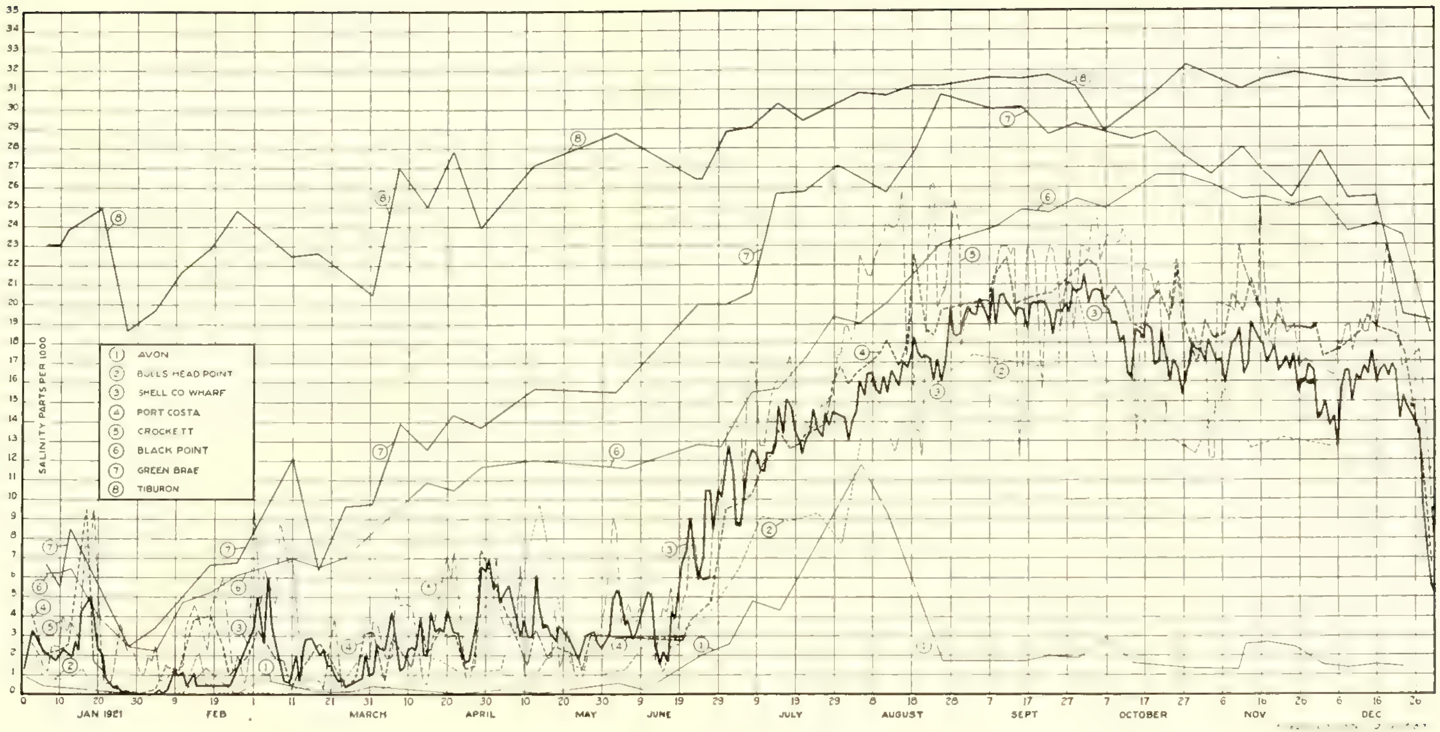

Fig. 93. Salinities in the northern arm of San Francisco Bay, 1921.

the width and depth of the channel at different points, and by differences in the seasonal discharge of the rivers, which is ordinarily more than five times as great during the first six months of the year as during the last six months (see p. 36, etc.). In the Carquinez Strait the annual range of variation in salinity is as great as from 0 to 27 parts per 1000. Salinities at several points in the upper bay during 1920-1922 are graphically shown in the appended charts (figs. 19, 93, 94).

The middle bay exhibits a set of conditions nearly the opposite of those just described. Its greater depth and volume and proximity to the open sea make for a condition of high and fairly constant salinity and for a minimum temperature fluctuation. Salinities at two localities in this portion of the bay during 1921-1922 are charted in figures 93, 94. These are not, unfortunately, the localities of maximum salinity, being considerably to the northward of the Golden Gate. Records of the *Albatross* investigations during 1912-1913 show the mean annual salinity at certain points in this area of the bay to be as high as 30 and even 31 parts per 1000 (Sumner, et al., 1914, p. 4).

The lower bay represents an environment intermediate between the two extremes just described. A great unbroken expanse of comparatively shallow water (mean depth 7.8 fathoms, as compared with a mean depth of 14.8 fathoms for the sector of the bay between Goat Island and Point Richmond), receiving no streams of any importance, the lower bay represents a complex of conditions peculiar to itself. The salinity is somewhat lower than that of the waters more proximal to the open sea, though at the same time it probably is subject to less daily and seasonal variation. Unfortunately, hydrographic investigations in this region have been extremely limited. The *Albatross* records show a mean salinity of from 28.47 to 29.14 at eight different stations south of Goat Island, the lowest figure recorded during a one-year period being 24.85 as compared with a maximum of 31.36 at the same station. For a very large stretch of water at the southern end of the bay no salinity records are available, but we are fairly safe in assuming that they would be consistent with the above figures, with possibly a slight increase in the mean during the summer, owing to the effect of evaporation (Sumner, et al., 1914, p. 85), and the opposite effect of seepage during and after the maximum run-off.

The temperature range is notably greater here than in the middle bay, owing largely to the influence of air temperatures on so large an expanse of relatively shallow water; but less, on the other hand, than in the upper bay, whose temperatures depend in considerable measure on those of the rivers tributary to it.

Temperature ranges in the three divisions of the bay can best be compared by reference to figure 95, where they are graphically represented.

Seasonal Distribution of Teredo with Reference to Fluctuating Conditions in the Upper Bay

The upper portion of San Francisco Bay, particularly the region of Carquinez Strait and beyond, affords an environmental complex of peculiar interest as regards *Teredo navalis*. Here the organism is subjected to conditions of stress—low and fluctuating salinity, much turbidity, and a wide range of temperature variation. Somewhere in this region occurs the combination of conditions which marks the limit of the activities of the animal.

The breeding season of this species in San Francisco Bay is practically co-extensive with the autumn period of minimal river discharge. In consequence, the free-swimming larvae make their appearance at just the time when salinities in the upper bay are highest, and the conditions most favorable for their survival. The tidal movement is

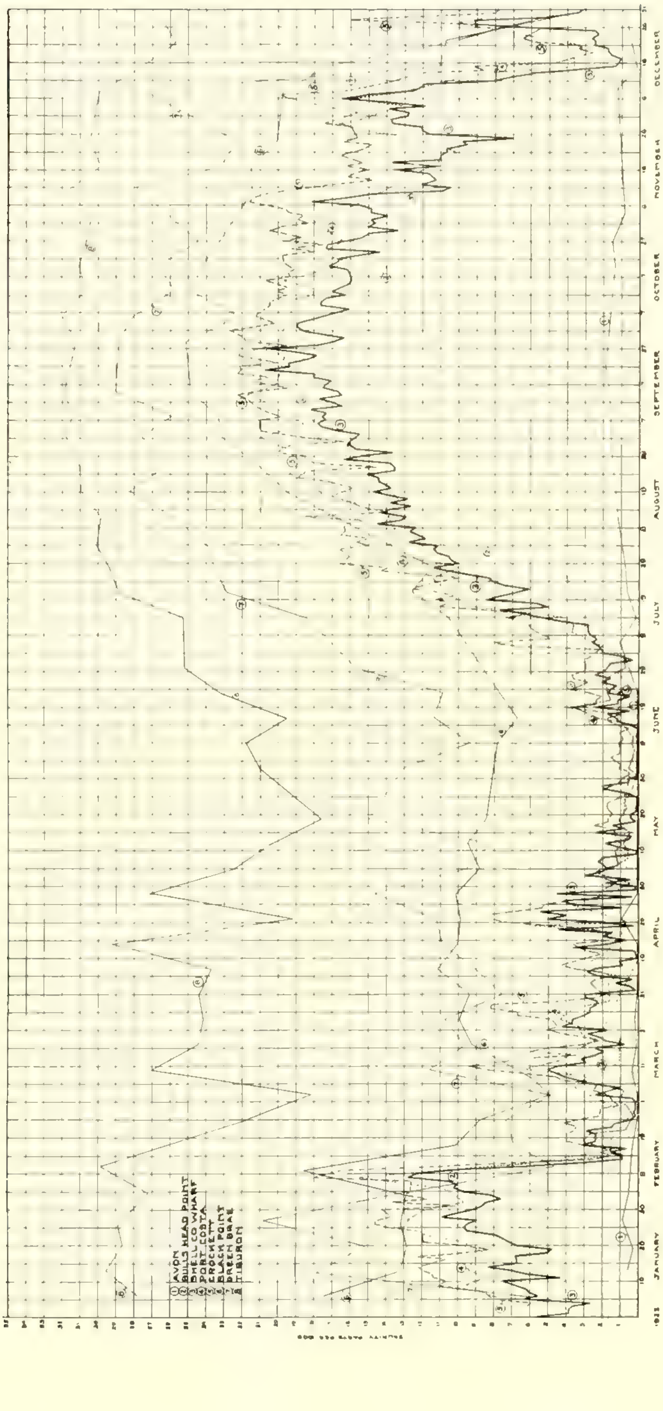

Fig. 94. Salinities in the northern arm of San Francisco Bay, 1922.

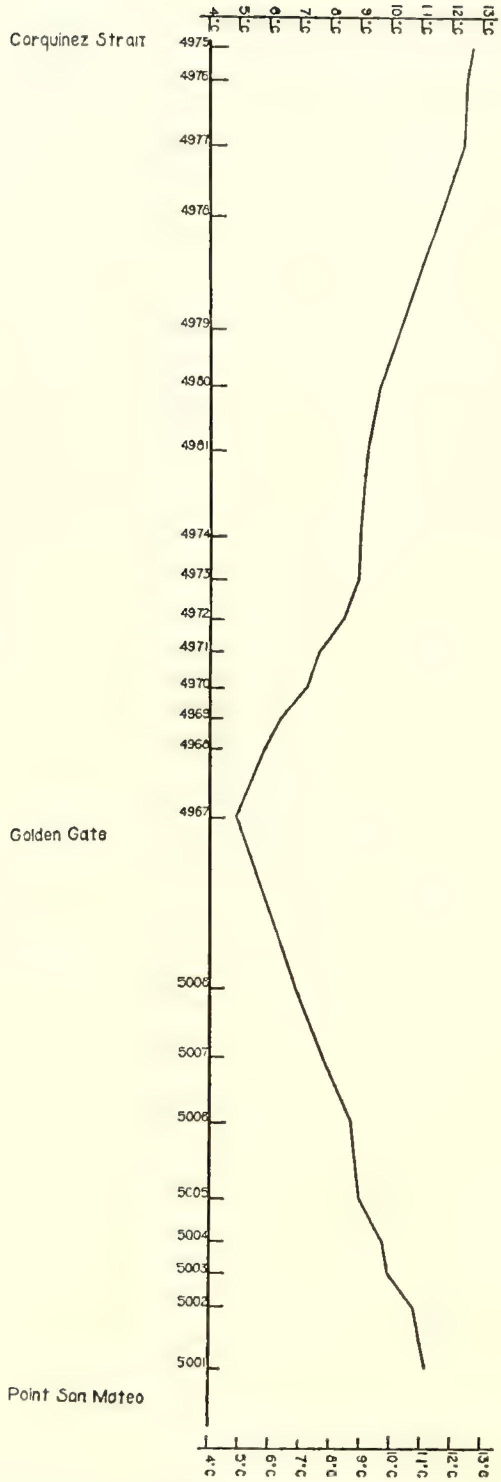

Fig. 95. Seasonal range of temperature in the three divisions of the bay. Numbers along the locality coordinate refer to hydrographic stations. (*After Sumner et al., U. C. Publ. Zool., 1914, Fig. C.*)

considerable in this region, the influence of the tides being observed far up the Sacramento and San Joaquin rivers. Through Carquinez Strait in particular the tidal currents rush with great velocity. Thus on each recurring high tide the larvae of *Teredo* have an opportunity to be carried far into the waters of Suisun Bay, the uppermost limit at which they will establish themselves depending on the conditions during the year in question.

With the recurrence of the flood season of winter and spring those organisms which have become established farthest up stream are killed off by the fresh water and the frontier of teredo activity is pushed back to a point which again varies with the conditions of different years. It becomes of interest therefore to note for a series of years the uppermost limit to which teredo extends during the autumn, and the uppermost point at which the organisms are able to survive during the following winter and spring, until the return of favorable conditions.

In the autumn of 1920, following two years of reduced rainfall, the activity of *Teredo* extended as far up as Antioch on the San Joaquin river. Reports of its occurrence at Rio Vista on the Sacramento river were not confirmed by acutal specimens. With the return of the winter flood period, however, all borers were apparently exterminated, not only in Suisun Bay, but also well down the Carquinez Strait. Examination of piling at several localities from January to April, 1921, showed no living *Teredo* above Crockett, which is thus established as the uppermost limit of survival during the winter of 1920-1921.

This winter was one of approximately normal rainfall and river discharge, and the following autumn (1921) was not favorable to the extension of *Teredo* into Suisun Bay. The initial settlement of larvae at Crockett and Port Costa was delayed a month as compared with the previous year, and no organisms were found farther up than Benicia, where a few small specimens, up to 1 cm. in length, were found in test boards on November 14. At Crockett, in 1922 as in 1921, *Teredo* survived the fresh water period of winter and spring, but in minimal numbers only. It is estimated that 90 per cent of the teredos at this locality were killed off between January and July, 1922.

In the autumn of 1922 *Teredo* is known to have gone upstream as far as the wharf of the Mountain Copper Company at Martinez, where some specimens reached a length of 10 cm. before being killed off by the returning flood waters. The organism did not reach Roe Island (opposite Bay Point), as a number of test boards planted at the Roe Island Light Station showed no attack during this season. There is evidence that some individuals survived the winter of 1922-1923 at Port Costa, although the great majority were killed off. One living specimen 29.2 cm. in length was found at this locality on December 4, 1923, which, from its size, is believed certainly to have been a survivor of the fall brood of 1922.

The autumn of 1923 was marked by a recurrence of conditions of increased salinity in the upper bay, and a renewed extension of the activities of *Teredo* in this region. On November 28th specimens 4 cm. or more in length were found in test timbers at the wharf of the Associated Oil Company at Avon, and there is evidence that some individuals established themselves during this season as far up as Pittsburg. No surviving specimens were found at the latter locality when a search for them was made on June 23, 1923, indicating that the limit of survival during the winter of 1922-1923 was at some point between Avon and Pittsburg. At Avon some specimens had reached a length of 7 cm. by June 1st, and appeared to be in healthy condition at that time. By the end of July it was found that they had seriously damaged the piling at this locality, as shown in figure 96.

It appears then that the conditions of low salinity lethal to *Teredo* recur each

flood season in Carquinez Strait or just above, at a point that is determined anew each year by rainfall and river discharge. The following experimental work (Blum, 1922) was undertaken with a view to determining the conditions of low salinity that are unfavorable to *Teredo navalis*, and further the conditions that are definitely lethal to the organism.

Effect of Low Salinity

Specimens were first acclimatized by placing them in standing water of a salinity of 15 parts per 1000 for two to four days. During this period a daily record was kept of the number of siphons extended from the specimen block, this number being taken as the original 100 per cent for the given specimen. The specimens were then changed to salinities of 0, 2, 4, 5, 6, 7, 8, 9, or 15 parts per 1000. A record was kept of the number of siphons extended from each specimen block during the periods of exposure (about three weeks) to these several lower salinities. Ten specimen blocks in individual aquaria were used in determining the average per cent of siphons extended by the

Fig. 96. Section of untreated fender pile from Avon wharf of Associated Oil Co. Pulled July 29, 1924.

teredos for each salinity tested. The number of siphons extended from each specimen block was recorded each day for a period of days after an apparent maximum had been reached which did not fluctuate markedly. Low records during this period, accompanied by unfavorable aquarium conditions, were discarded. These values were averaged for each specimen and the per cent of siphons extended was computed by comparison with the number of siphons originally extended from the same block in a salinity of 15 parts per 1000. The average per cent for each salinity was computed from the average of the ten specimens. The per cent of siphons extended in a salinity of three parts per 1000 was determined separately under similar conditions, but during a shorter period of exposure.

The percentage of siphons extended from control blocks exposed during the

experiment to a salinity of 15 parts per 1000—which should obviously be 100 per cent—was found to be only 92 per cent of that in earlier tests. If we assume that 8 per cent of the individuals were killed off by the conditions of life in the aquaria, we may raise all the values 8 per cent. This produces a curve represented by the dotted line in the graph (fig. 97) and is probably more typical than the curve obtained from the actual values computed from the records of the experiment without this correction.

The individual values from which the percentages for the curve were computed show deviation of 15 per cent from the mean in some cases, and at best the curve is

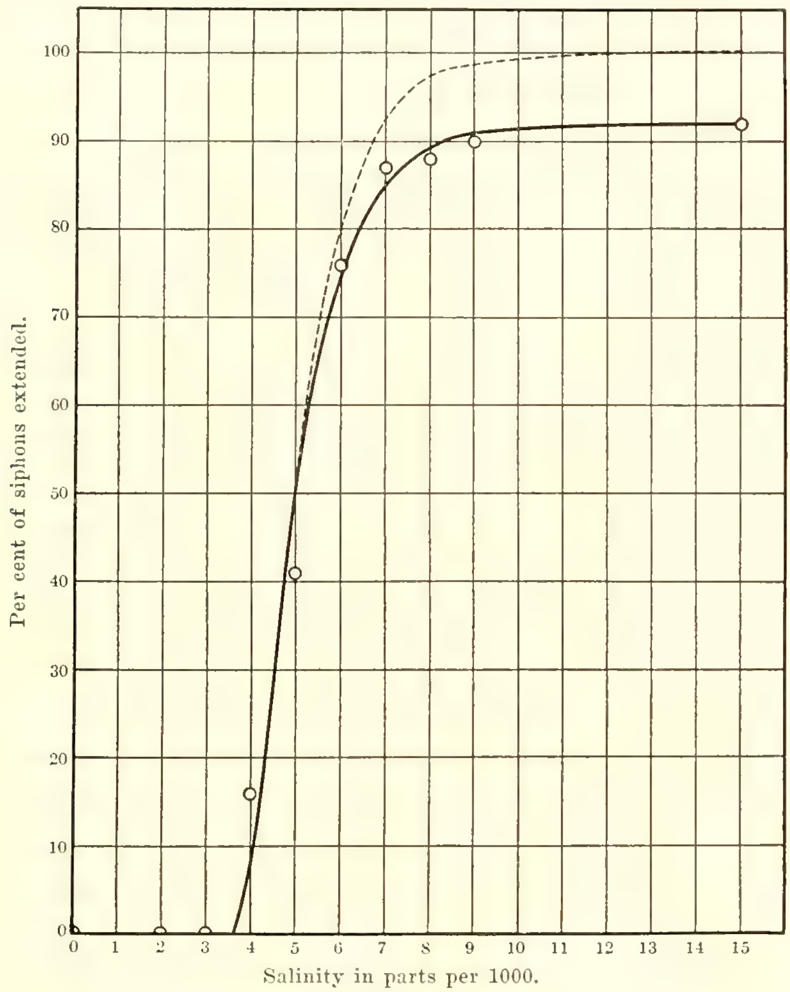

Fig. 97. Activity of *Teredo navalis* in water of various salinities.

only an approximation of actual conditions. Had it been possible to use a salinity nearer the optimum for the organism (probably about 20 parts per 1000) in determining the 100 per cent value for the graph, the position of the curve would have been changed to some extent. The decrease in per cent of siphons extended, between salinities of 15 and 9 parts per 1000, is very slight, however, and it may be expected that the increase between the salinity of 15 parts per 1000 and the optimum will be correspondingly small. None of these deviations will greatly alter the shape or position of the curve.

The curve indicates that the activity of the borers is nearly or quite as great in a

salinity of 9 parts per 1000 as in higher salinities. In salinities below 9 parts per 1000, the per cent of functioning individuals becomes less, and decreases more rapidly as the salinity is decreased, until at 3 parts per 1000 there are no siphons extended. The curve descends rather gradually from 9 to 6 parts per 1000 and then slopes abruptly down to 4 parts per 1000. This rapid decrease in the number of siphons extended in salinities below 6 parts per 1000 indicates that, below this point, the vital functions are abruptly interfered with in a large number of individuals.

The reduction of activity in these lower salinities is also indicated by the cessation of boring activity. The degree of this activity was estimated from the amount of chips ejected which collected on the bottom of the aquarium. In the salinities of 7 parts per 1000 and above, boring was found to be very active, in 6 parts per 1000

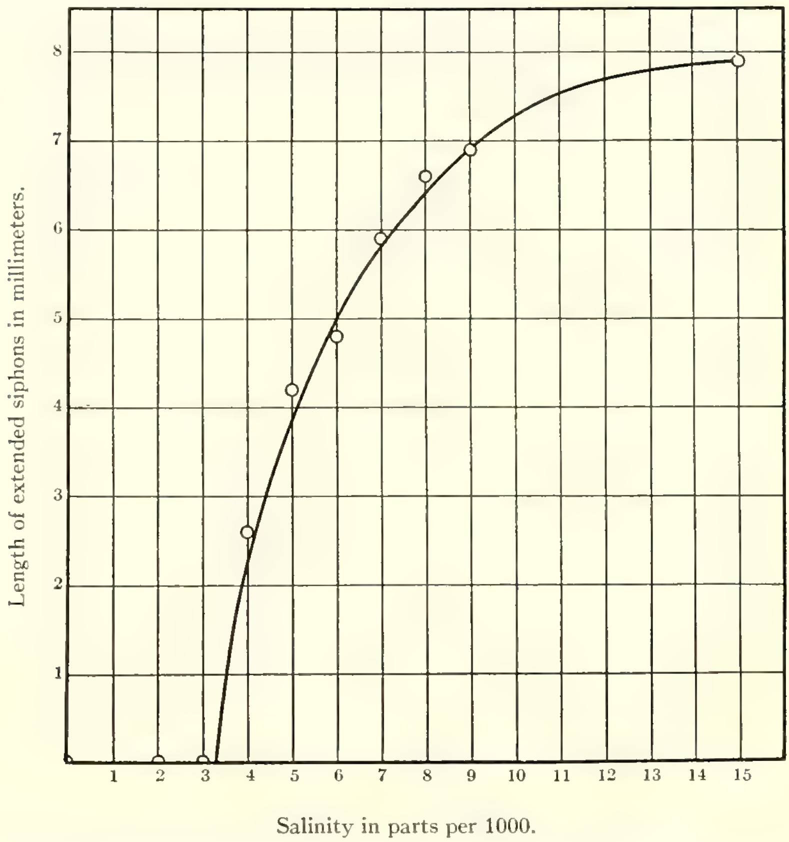

Fig. 98. Graph representing length to which siphons of *Teredo navalis* are extended in water of various salinities.

slightly less, in 5 parts per 1000 very rare, while in 4 parts per 1000 it was never observed in the aquaria.

There was also an accompanying change in the sensitivity of the siphons, these retracting rapidly in the salinities of 6 and 7 parts per 1000, moderately in 5 parts per 1000, and slowly in 4 parts per 1000.

Again, there was a marked change in the length to which the siphons were extended, which is illustrated in figure 98. This curve shows a gradual decrease in the length of the siphons with decrease in salinity, the decrease per part per 1000 becoming greater as the salinity decreases.

The Lethal Salinity

The foregoing observations indicate a general interruption of function in salinities below 6 parts per 1000, while below 4 parts per 1000 there is little or no activity. We may expect that above this critical range (4 to 6 parts per 1000) the teredos are able to continue to live and function, as regards salinity, while below this range the organisms will die if exposed long enough. The salinity below which the average individuals are unable to live may be called the *lethal salinity*. This salinity has been more accurately placed at 5 parts per 1000 by the following experiments.

Teredos were exposed by splitting away the outer surface of the specimen blocks and breaking away the thin shell around the pallets, so that the animals were unable to plug themselves up in their burrows. Individuals exposed in this manner lived for 11 days in slowly running water of 5 parts per 1000 salinity, after which time the results were obscured by fouling of the aquaria. The activity of these teredos as manifested by the sensitivity of the siphons at the end of this time was equal to that of specimens in 6 and 15 parts per 1000 salinity, as is shown in table 36.

TABLE No. 36

ACTIVITY OF TEREDO NAVALIS, EXPERIMENTALLY EXPOSED IN VARIOUS SALINITIES.

	Salinity—parts per 1000							
Days	0	1	2	3	4	5	6	15
0	0	0	slow	slow	moderate	rapid	rapid	rapid
1	dead	0	slow	slow	moderate	rapid	rapid	rapid
2	....	dead	slow	slow	moderate	rapid	rapid	rapid
3	....	....	dead	0	slow	rapid	rapid	rapid
4	....	....	....	dead	slow	rapid	rapid	rapid
5	....	....	....	....	slow	rapid	rapid	rapid
6	....	....	....	....	0	rapid	rapid	rapid
7	....	....	....	....	dead	rapid	rapid	rapid
8	....	....	....	....	....	rapid	rapid	rapid
9	....	....	....	....	....	rapid	rapid	rapid
10	....	....	....	....	....	rapid	rapid	rapid
11	....	....	....	....	....	rapid	rapid	rapid

Individuals exposed to salinities below the lethal (5 parts per 1000) were killed off very rapidly, as is shown in table 37. The criterion of death used in these experiments was the first appearance of degeneration of the tips of the siphons. As soon as this degeneration appeared, the specimen blocks were changed to water of a salinity of 15 parts per 1000, but the animals never revived after this degeneration had begun.

Harington (1922) reports experiments on the effect of low salinities upon the larvae of a teredo, probably *T. norvegica*. He shows that these larvae were able to survive for at least a short time in salinities as low as 10 parts per 1000, although swimming was inhibited below 17.5 parts per 1000. No observations of this kind have been made on the larvae of *T. navalis*. Since *T. norvegica* is usually found in open sea water (i.e., water of a salinity of 35 parts per 1000 or thereabouts), however, it is probable that the larvae are less adapted to low salinity than are the larvae of *T. navalis*, which inhabits brackish waters. It may be expected that the larvae of the latter form might be able to live in approximately the same salinities as the adult.

TABLE No. 37

SURVIVAL OF TEREDO NAVALIS, EXPERIMENTALLY EXPOSED IN VARIOUS SALINITIES

Salinity parts per 1000	Days of Survival	Average temperature in degrees C°	Remarks
0	1	17	2 determinations
1	2	17	1 determination
2	3	17	1 determination
3	4	16	1 determination
4	7	17	1 determination
5	..	17	Teredos still active at end of 11 days
6	..	17	
15	..	17	

Natural Protection Against Unfavorable Salinity

Although teredos exposed by splitting away the block around the pallets were soon killed when placed in salinities less than 5 parts per 1000 (see table 37), individuals in specimen blocks which had not been exposed in this manner lived for much longer periods in the same salinities. Table 38 gives the per cent of organisms surviving various periods of exposure to salinities of 0 and 2 parts per 1000.

Table 39 gives comparative results from tables 37 and 38, showing that, in the same salinities, unexposed teredos lived much longer than exposed individuals. The organisms therefore received some protection from their burrows, through their ability to prevent the entrance of water from the outside by plugging the burrow entrance with the pallets when the salinity of the water fell below the danger point (5 parts per 1000), and at the same time to retain a quantity of salt water within their burrows.

Factors Limiting Protection

We may expect that if the water within the burrow were diluted to a point much below the lethal salinity (5 parts per 1000), the teredos would be killed, since the animals die in a short time when directly exposed to water of less salinity. Such a process of dilution is indicated by the following experiment.

A specimen block containing teredos was removed from water of 15 parts per 1000 salinity and placed above water in a closed aquarium functioning as a moist chamber. In this way, evaporation of the water in the wood was restricted, but no dilution of the water in the burrows was possible. At the end of twenty-two days, the specimen block was placed in salt water and approximately 50 per cent of the original number of teredos extended their siphons. This was a greater survival than that in water of 0 and 2 parts per 1000 salinity for the same period of time. Table 39 shows the survival periods under different experimental conditions.

Since at the end of twenty-two days a greater percentage of teredos survived in the block not directly surrounded by water than in the blocks exposed to water of either 0 or 2 parts per 1000 salinity, we may assume that in the latter case the water within the burrows was diluted by the fresh water from the outside.

TABLE No. 38

SURVIVAL OF TEREDO NAVALIS IN STANDING WATER* OF LOW SALINITY IN AQUARIA

Salinity** parts per 1000	Days exposed	Per cent of siphons extended in sea water after this period	Remarks
0	7	100	....
0	10	100	....
0	15	50	....
0	16	15	....
0	18	30	....
0	21	5	....
0	24	0	Average of 4 specimens
2	13	100	....
2	15	100	....
2	18	100	....
2	21	33	....
2	22	32	Average of 3 specimens
2	24	22	Average of 2 specimens
2	26	0	....

*Water renewed every two days by passing stream of same salinity through aquaria for a few moments.
**Specimens acclimatized in 15 parts per 1000, and changed directly to lower salinities.

TABLE No. 39

SURVIVAL OF TEREDO NAVALIS UNDER VARIOUS EXPERIMENTAL CONDITIONS IN AQUARIA

Conditions	Salinity	Days exposed	Per cent of individuals surviving
Teredos exposed by cutting away mouth of burrow..	0	1	0
	2	3	0
Unexposed teredos.......	0	21	5
	2	22	32
Unexposed teredos, block above water in closed aquarium..............	..	22	50

The process involved in this dilution of the water in the burrow is probably one of diffusion through the wood of the pile and perhaps between the pallets at the mouth of the burrow. It is also possible that the organisms may continue to draw in small quantities of water through their siphons, thus gradually diluting the water in the burrow; but this is not probable, since it was found that teredos were killed more rapidly by running fresh water than by standing fresh water, which could hardly be

explained by such a process. The above observation is more readily explained on the basis of diffusion, as the speed of this process would be increased by motion and change of water. The following experiment shows some results obtained with specimens in running water.

A series of aquaria was arranged so that currents of fresh water of three different rates of flow could be passed through them. The rates of flow were not accurately measured, but had the following relation: A>B>C. A was the discharge of a three-quarter inch pipe, C a flow of approximately five gallons per hour, and B intermediate between these currents. Specimen blocks containing teredos were exposed in these aquaria and in aquaria containing standing fresh water. Two other specimens were prepared from ordinary specimen blocks by covering the split surfaces and cut ends of the block with a thin coating of paraffin. These specimens were exposed simultaneously with the untreated specimens in aquaria through which currents B and C were passing. All the specimens contained approximately the same number of live teredos at the beginning of the run. After seven days the specimens were changed to water of 15 parts per 1000 salinity. Table 40 gives the approximate number of individuals surviving under the various conditions.

TABLE No. 40

SURVIVAL OF TEREDO NAVALIS IN RUNNING AND STANDING FRESH WATER

Rate of current*	Number of individuals alive at end of 7 days		Mean temperature in degrees C°
	Cut surfaces paraffined	Untreated	
A	....	0	19
B	....	0	19
C	....	30	16
C	....	30	11
Still Water	....	50	8
Still Water	....	60	8
B	15	......	19
C	30	......	16

*A>B>C.

Table 40 shows that the survival was greater in standing water than in running water, and greater in slowly running water than in swiftly running water. Specimens having the cut surfaces protected by a coating of paraffin, and therefore having less surface exposed for diffusion of water, show a greater survival than untreated specimens. The explanation of the dilution of the water in the burrow by a process of diffusion through the wood accounts for the above results, since the rate of diffusion would be expected to increase with the rate of flow of the current. This would shorten the time necessary for dilution of the water in the burrow, a condition which would be followed by the death of the teredos. The speed of such a process would also be decreased by reduction of the surface of the specimen by covering the cut surfaces with paraffin.

Table 38 shows that teredos lived longer in specimen blocks in water of 2 parts per 1000 salinity than in zero salinity. This may be due to the fact that diffusion takes place less rapidly between solutions nearer the same concentration than between solu-

tions having a greater difference of concentration. Thus the dilution of the water in the burrow would take place more slowly when the blocks were surrounded by water of 2 parts per 1000 salinity than when surrounded by water of zero salinity and the teredos would survive for a longer period.

Teredos in the piles at Crockett have survived greater periods of low salinity during the past three years than have the teredos under any conditions of low salinity in the aquaria (see tables 38 and 41). The short period of survival in the latter case may be due, however, to the greater relative surface exposed for diffusion in the specimen blocks than in piles. Besides having their cut surfaces exposed in most cases, these blocks were scrubbed free of barnacles and other marine growths which cover the exterior of all piles. Thus there was a relatively larger surface exposed for diffusion, including the face of the block, the split surfaces, the open ducts of the wood at the cut ends, and the very large surface exposed by the opening up of many burrows in cutting the block. As is shown in table 40, more teredos survived low salinities when the cut surfaces of the blocks were covered with paraffin, although this covering did not adhere closely in some places and was thus an imperfect seal. There must also be a slight leakage through the pallets although they fit tightly and form a very effective plug.

At times during the period of low salinity at Crockett, when several piles were pulled at the same time from the same locality it was found that there was a marked difference in survival in teredos from different piles. With conditions apparently the same for all the piles, it seems reasonable to assume that the difference of survival was due to differences in the porosity of the wood in the piles, which would allow diffusion to take place more rapidly in some piles than in others. A markedly greater percentage of teredos survives in a hard, close-grained pile than in one of a more soft and spongy texture. The most plausible explanation of this is that in the former case the salinity of water in the burrow of the animals is not so soon reduced to the lethal point by gradual filtering in of fresh water during a period of low salinity.

Although the above evidence is not conclusive, the explanation given seems to be the only one which accounts for some of the phenomena observed. Hence it seems reasonable to assume that when plugged up in their burrows teredos are killed only by a gradual reduction in salinity of the water in the burrow, and that this process takes place in part by diffusion through the wood.

Survival Period or Lethal Stretch

An explanation of the above process becomes important if we wish to predict the survival of teredos by observation of the salinity of the water from day to day. In a daily salinity record such as is represented by figure 99, periods of survival or lethal stretch must be measured as periods during which the salinity remains below 5 parts per 1000, as when the salinity rises above this point the teredos are able to take in a fresh supply of salt water. Fluctuations of salinity during such periods must influence the rate of dilution of the water in the burrow, but are of little importance for predicting the survival of the organisms.

During the winter of 1921-1922 a daily record was kept of the salinity of the water in Carquinez Strait. Samples were taken during the day at high and low tide, from the surface and from a depth of 14 feet. Samples were also taken at two points about one-eighth mile apart, as it was found that differences in the salinity at these two points occurred frequently because of currents and eddies. In preparing the salinity graph, figure 99, the maximum and minimum records from all samples for each day have been plotted.

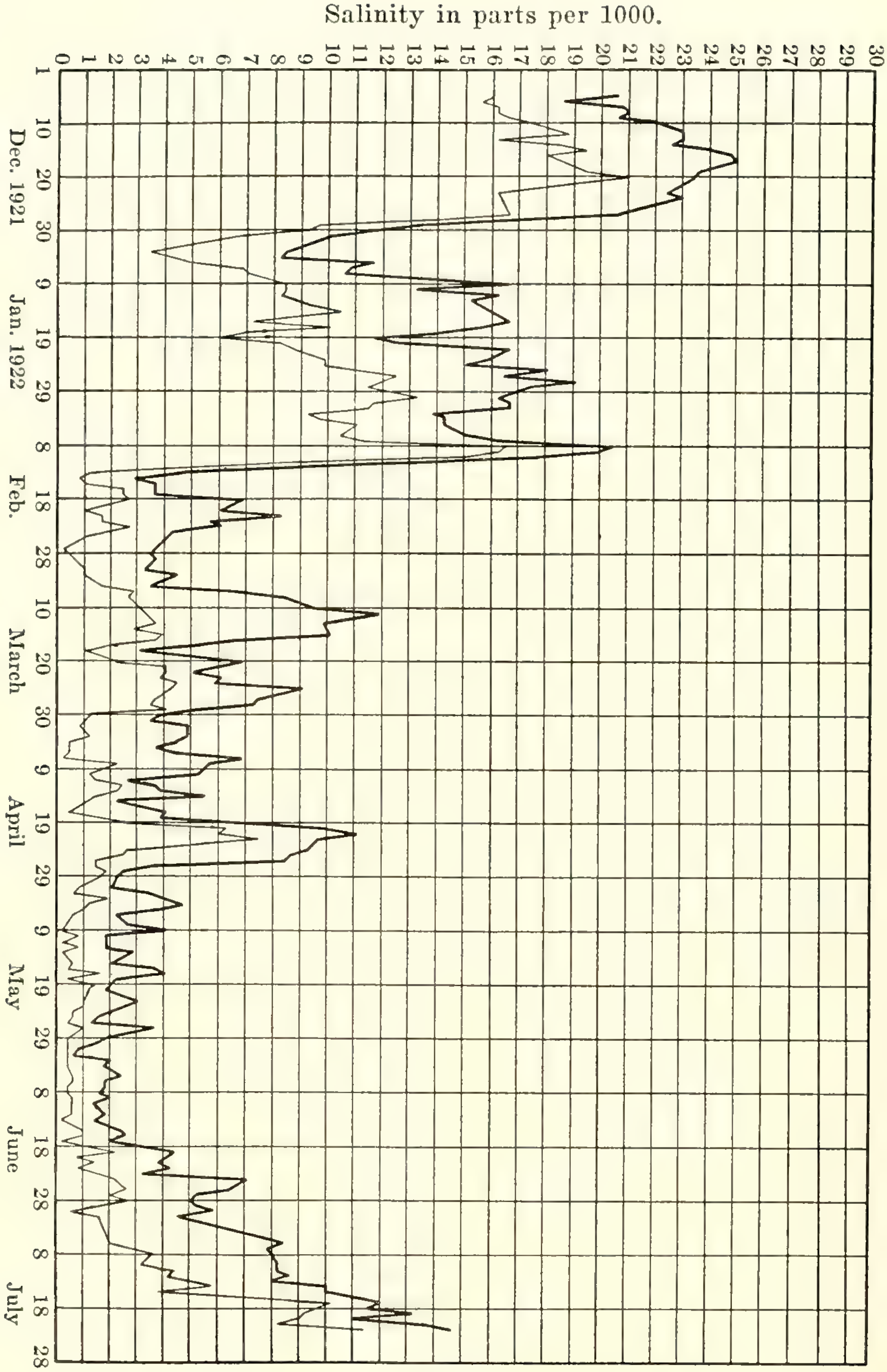

Fig. 99. Graph of salinity of water at Crockett during the season of 1921-1922.
Heavy line, maximum salinity. Light line, minimum salinity.

TABLE No. 41

SURVIVAL OF TEREDO NAVALIS IN PILES AT CROCKETT DURING PERIOD OF LOW SALINITY, SEASON OF 1921-1922

Date pile was pulled	Period of days below 5 parts* per 1000	Period of days below 4 parts** per 1000	Period of days below 3 parts*** per 1000	Per cent of individuals surviving
May 13	16	....	....	100
May 18	21	1	....	90
June 5	39	19	9	50
June 12	46	26	16	40
June 26	50	33	23	10
July 29	58	33	23	10

*Salinity remained below 5 parts per 1000 from April 26 to June 24.
**Salinity remained below 4 parts per 1000 from May 17 to June 19.
***Salinity remained below 3 parts per 1000 from May 27 to June 19.

Reference to figure 99 shows that during that season (1921-1922) the salinity remained below 5 parts per 1000 from April 26 to June 24, below 4 parts per 1000 from May 17 to June 19, and below 3 parts per 1000 from May 27 to June 19.

Table 41 shows the survival of teredos in piles pulled from the fender lines at Crockett, at intervals during the period of low salinity.

It appears from table 41 that 10 per cent of the borers survived a stretch of 58 days of salinity below 5 parts per 1000. During May, however, several peaks occurred which reached salinities of 4 parts per 1000 or more (see fig. 99).

It has since been found also that bottom salinities at Crockett (cf., figure 100, showing surface and bottom salinities at Martinez, where conditions are quite similar to those at Crockett) may be from two or three to six parts per thousand greater than salinities at the surface. As the depth along the wharf at Crockett is from 25 to 40 feet, samples taken at a depth of 14 feet, on which table 41 is based, do not adequately represent the bottom conditions.

It has been a matter of repeated observation at Crockett that teredos in the lower end of a pile, in the region of the denser water, will survive long after all those at higher levels in the same pile have been killed off. Of a considerable number of piles at this locality examined in the spring and summer of 1922, the highest level at which any survivors occurred at the end of the fresh water period was 17 feet above the mud, in water 33 feet deep at low tide. It would appear therefore that the conditions represented in figure 99 and table 41, based on samples taken at a depth of 14 feet, represent the conditions which are just lethal to the organisms. At this level all died. A few feet lower in the pile a few survived.

Our experiments have indicated 5 parts per 1000 as the average lethal salinity, but it was also observed (fig. 98) that a small proportion of the organisms— those individuals most highly resistant to conditions of low salinity—could extend their siphons and carry on their functions, at least in part, for some time in a salinity of 4 parts per 1000. This fact may explain the survival of a few individuals at a level just below that represented by the salinity figures given. It is further probable that, since samples were not always taken at the major tide of the day, the salinity may have reached 5 parts per 1000 on some of the days when our salinity record shows only

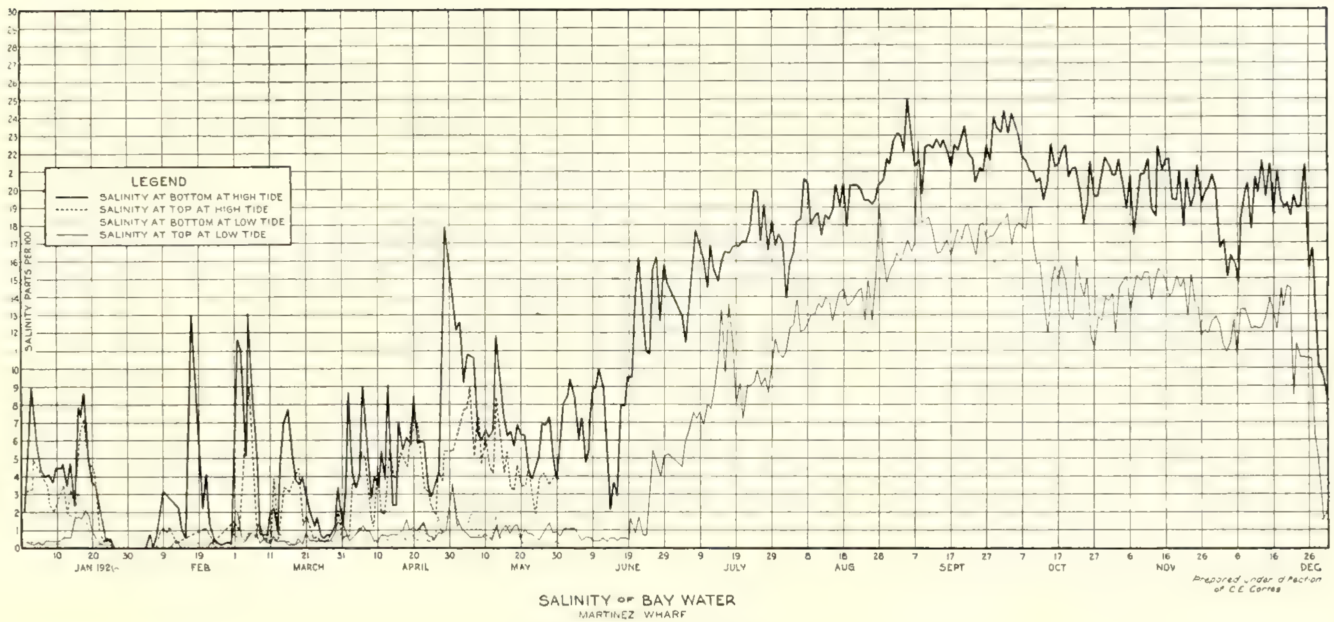

Fig. 100. Salinity at surface and bottom of the Bay, Martinez Wharf.

4 parts per 1000. Thus it may be advisable to assume 4 parts per 1000 as the critical salinity in interpreting the results given in table 41. The real stretch seems to have occurred during the period when the salinity was below this point, since, in the piles examined, 50 per cent of the borers were dead at the end of 19 days, 60 per cent at the end of 26 days, and 90 per cent at the end of 33 days. This corresponds more closely with some of the results obtained in the aquaria (see table 38).

From this interpretation of the results an estimate of one and one-half months of a salinity below 4 parts per 1000 as the period required for the destruction of all the teredos seems reasonable, and has been borne out by subsequent observations. A careful study of the salinity graphs for this and other localities in the upper bay indicate that no teredos have survived a period of stress as great as this.

During the years 1859-1869, Dutch investigators made observations upon *Teredo navalis* along the coast of the Netherlands and in the Zuider Zee. Frequent records were taken of the salinity at various points, and these are noted in a series of reports (Vrolik, et al., 1860-1863; Van Oordt, et al., 1864, 1865, 1869). From these records it appears that the lowest salinities occurred during the year 1861 at Niewendam on the Ij. During that year the salinity averaged 7.67 parts per 1000 of sodium chloride (8.39 parts per 1000 total salts). The lowest record for the year was 6.17 parts per 1000 sodium chloride (6.74 parts per 1000 total salts). In this year the salinity remained below 9 parts per 1000 from May 1 to December 31, and during the year the borers were plentiful in the region. *Teredo navalis* has survived much lower salinities at Crockett than those recorded at Niewendam. It appears that the salinity was never low enough at the latter place to exterminate the borers, although it may have reduced their activity during certain periods.

Resistance to Sudden Changes in Salinity

Reference to fig. 99 shows that the teredos at Crockett experienced many sudden changes of salinity prior to the long period of low salinities in May and June. Differences of four to six parts per 1000 between the maximum and minimum salinities for the same day occur frequently. There was a drop of seven parts per 1000 on two days in December, and in February a drop of thirteen parts per 1000 in three days. The borers survived all the changes which occurred prior to the prolonged period of low salinity in May and June.

It has been observed, in the aquaria, that teredos which have been forced to plug up their burrows because of reduced salinity revive very rapidly when placed in salt water. One hour is generally sufficient for resumption of activity by all the living individuals, the siphons being extended and normal activity having begun by the end of this time.

Effect of Hydrogen-ion Concentration and Dissolved gases

While temperature and salinity are recognized as factors of prime importance in the study of the relation of a marine organism to its environment, certain other physico-chemical conditions of the water need also to be taken into account. Among these are the amount of dissolved oxygen present, this gas being necessary for the respiration of aquatic organisms; the amount of dissolved hydrogen sulfide, which is poisonous when present in more than minute quantities; and the hydrogen-ion concentration of the water, which is a measure of its acidity or alkalinity.

The concentration of hydrogen ions is commonly expressed in terms of the

Sörensen unit (pH), which is defined as the logarithm of the reciprocal of the hydrogen-ion concentration:

$$pH = \log \frac{1}{[H^+]}$$

A neutral solution (i. e., a solution in which hydrogen-ions and hydroxyl-ions are present in exactly equal concentrations) has a Sörensen value of pH 7. A solution in which the pH value is below 7 is acid in its reaction; above pH 7 the reaction is alkaline. It should be noted that an increase in the pH value means a *decrease* in the concentration of hydrogen-ions, since the expression chosen is the logarithm of the *reciprocal* of the hydrogen-ion concentration.

Sea water is normally slightly alkaline in reaction (say, between pH 7.5 and pH 8.5), due to the presence and "buffer" effect of the carbonates and bicarbonates of calcium and magnesium. It is rendered less alkaline and possibly even slightly acid in the presence of large amounts of carbon dioxide. Any considerable change in the hydrogen-ion concentration of the water is likely to be deleterious or even fatal to marine organisms, either directly, or indirectly through associated changes in the physico-chemical complex of the environment.

As nothing was known regarding the dissolved gases and hydrogen-ion concentration of the waters of San Francisco Bay, and their possible influence on the breeding and distribution of *Teredo* and its allies, it was considered desirable to make some study of these conditions at different localities within the bay. In the summer of 1923 such an investigation was accordingly undertaken. The localities selected were Crockett, Dumbarton, the Oakland Mole, the San Francisco Ferry Building, and the Fort Scott Mine Dock (near Fort Point). Surface and bottom water samples were taken at approximately hourly intervals through a twenty-hour (minimum) period at each station, except at Dumbarton, where difficulty of access and inadequate facilities made it impossible to carry out the full series of observations. This program was repeated for a total of three times at each locality. The factors studied were salinity, temperature, dissolved oxygen, dissolved hydrogen sulfide, and hydrogen-ion concentration.

The results of this survey are shown in the accompanying graphs (Figs. 101-105), which are largely self-explanatory. A detailed analysis of the data in their broader biological bearing has been given elsewhere (Miller, Ramage and Lazier, Univ. Calif. Publ. Zoology, 1927). A brief summary may be given of the facts bearing on the present discussion.

At all localities the water was found to be more than four-fifths saturated with oxygen. Occasional instances of saturation or supersaturation were found, such conditions being the immediate effect of rapid photosynthesis by marine vegetation on warm, sunny days. During the period of the investigation (about three weeks) there was a progressive increase in the per cent of saturation with dissolved oxygen from week to week, which was correlated with a progressive increase in temperature and number of hours of sunshine.

The amount of dissolved hydrogen sulfide was usually very small, the maximum value encountered being 0.42 c.c. per liter, at Crockett. The average for the entire bay was only 0.13 c.c. per liter.

The Sörensen values were found to be surprisingly uniform throughout the bay, the average ranging from pH 7.68 at Crockett to pH 7.95 at Fort Point. The lowest value encountered, excluding certain samples taken at the mouth of a sewer, was

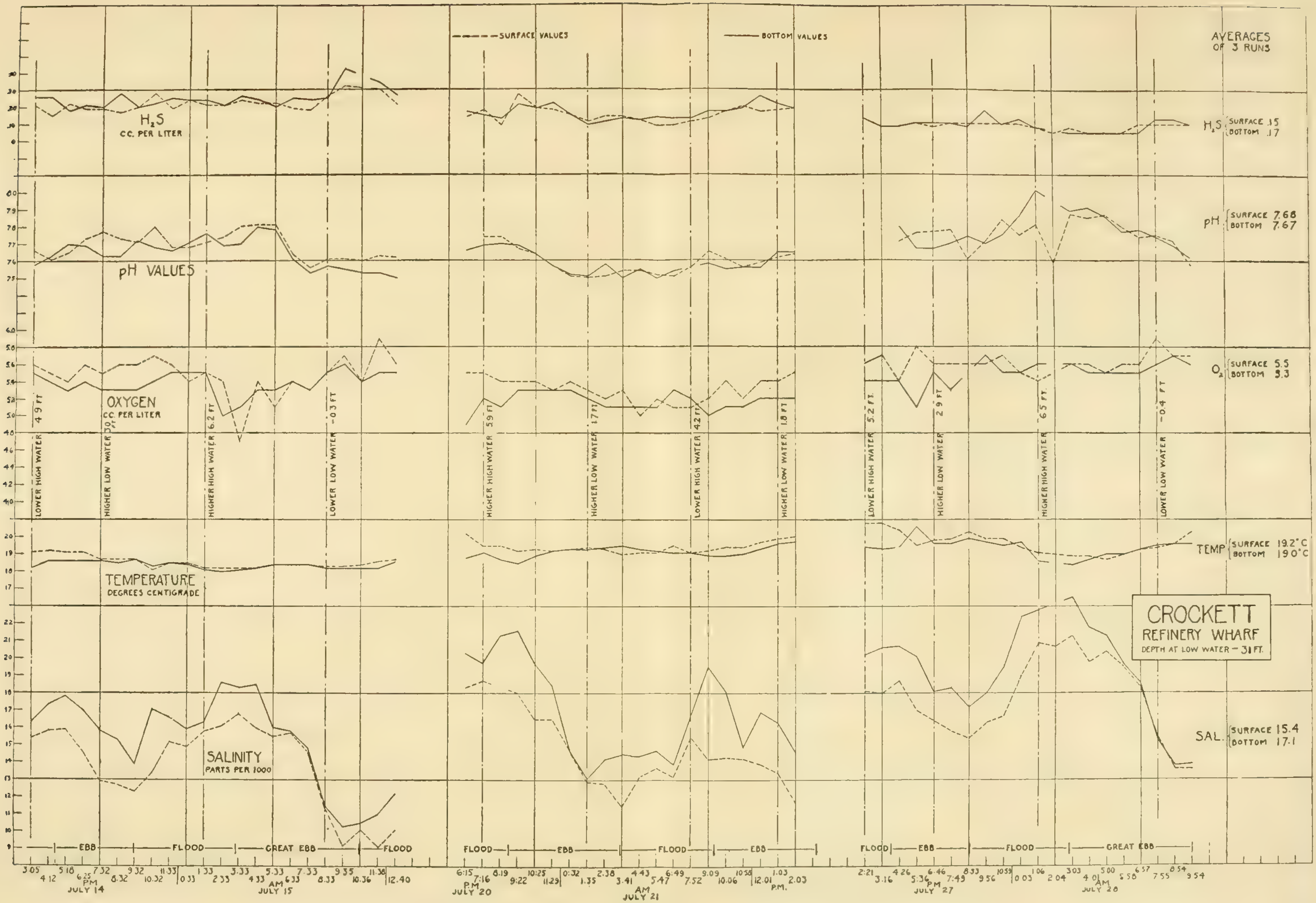

Fig. 101. Graphs of physical and chemical conditions in Carquinez Strait, at Crockett, in July, 1923.

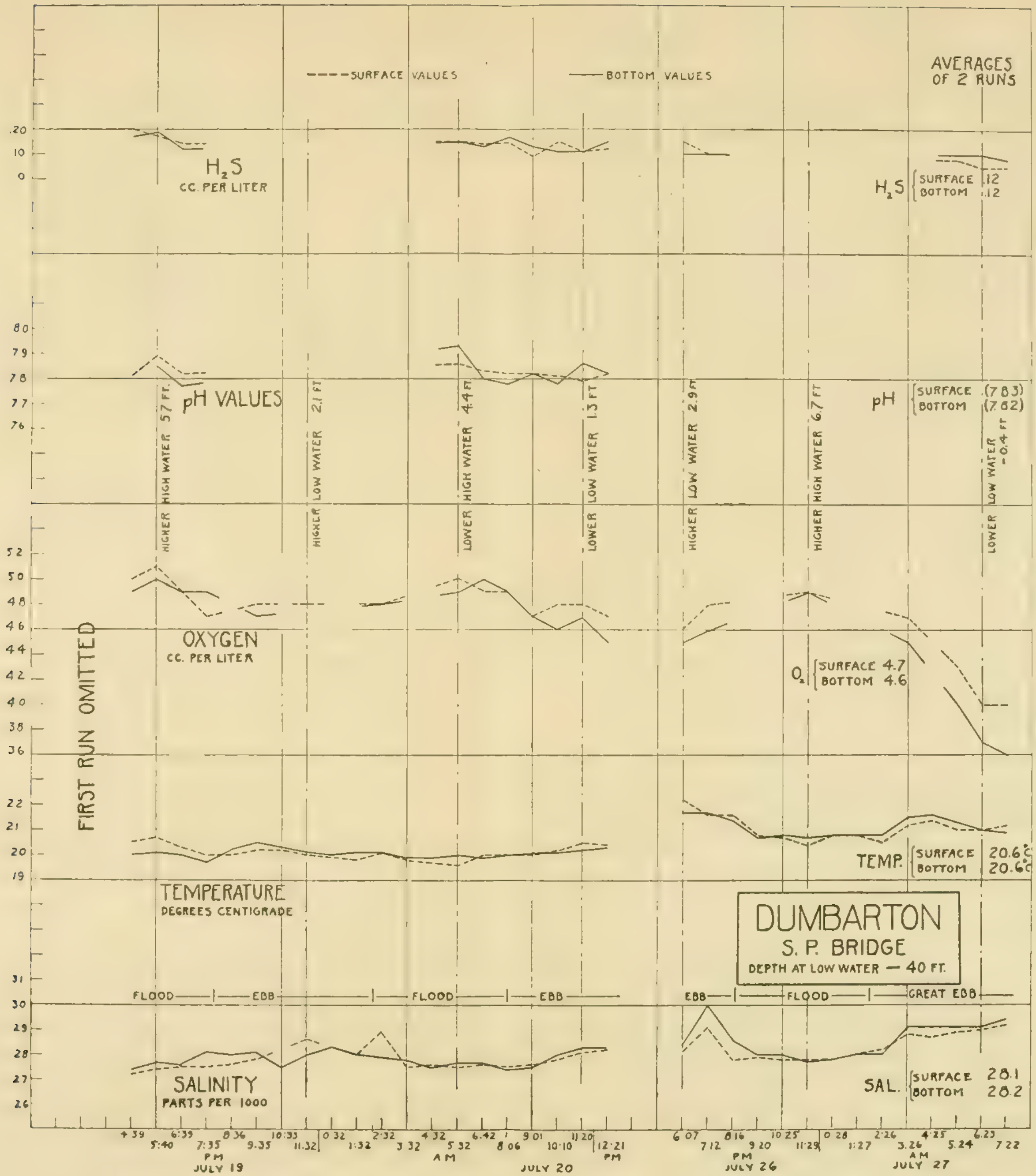

Fig. 102. Graphs of physical and chemical conditions in San Francisco Bay, at Dumbarton, in July, 1923.

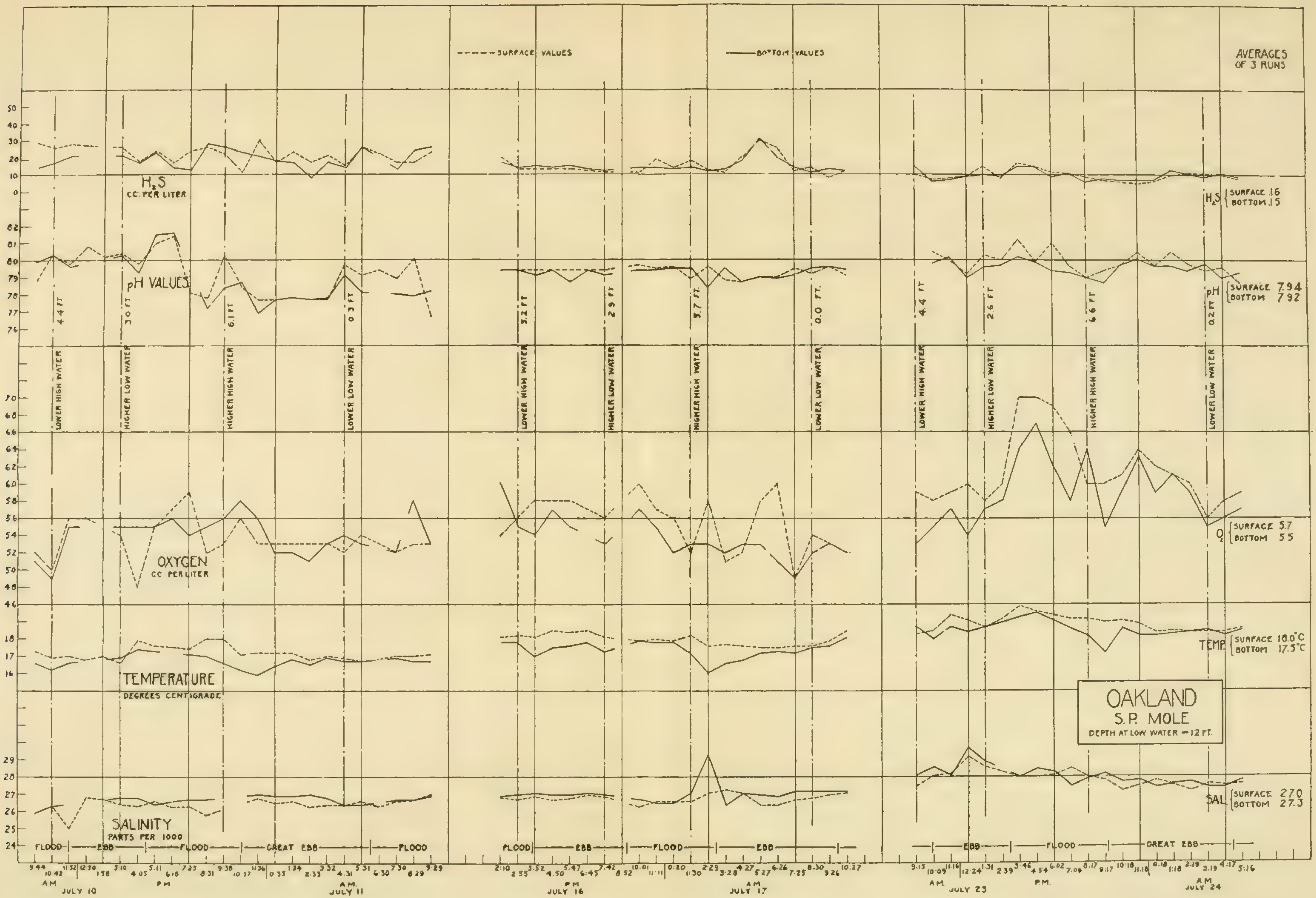

Fig. 103. Graphs of physical and chemical conditions in San Francisco Bay, at the Oakland Mole, in July, 1923.

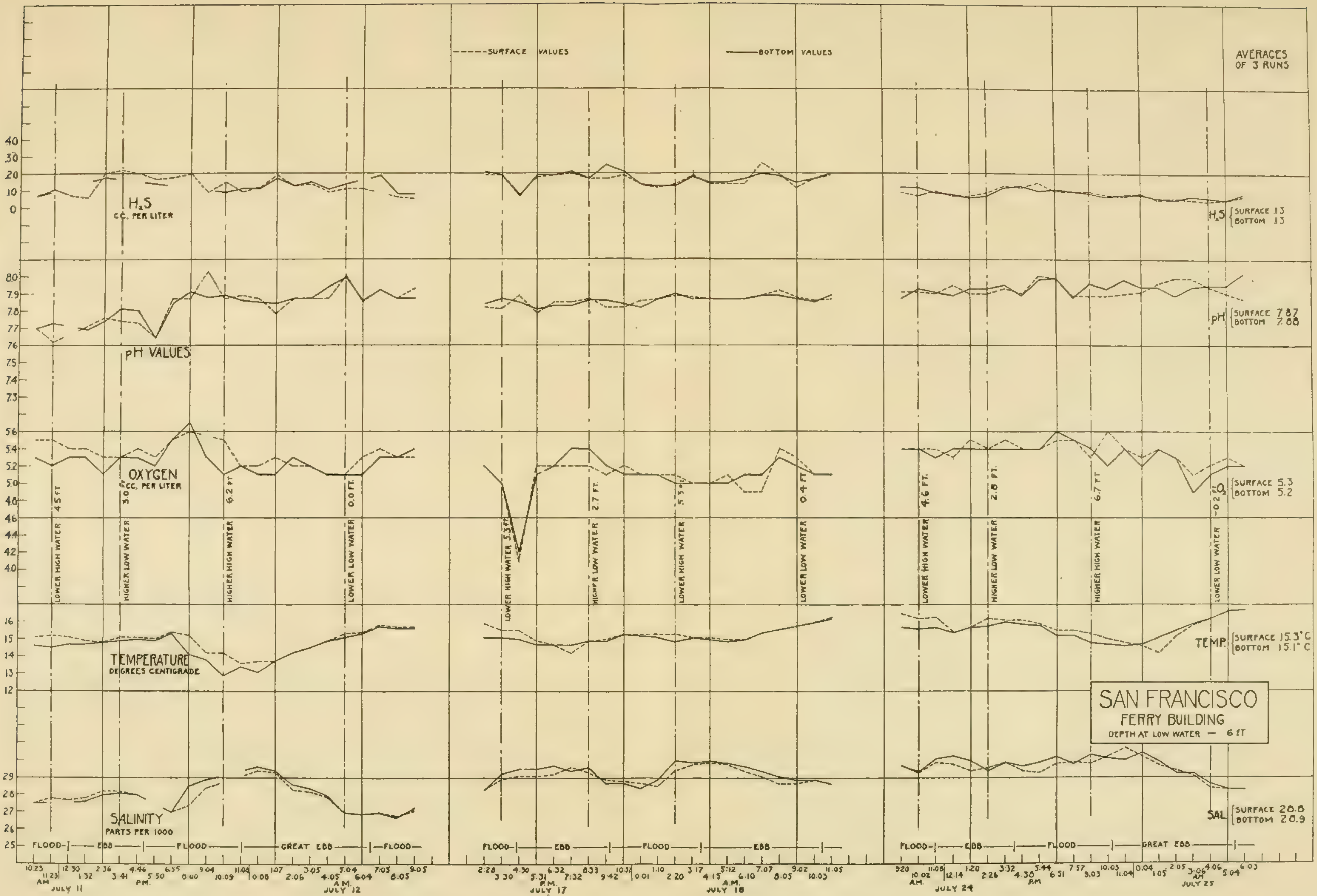

Fig. 104. Graphs of physical and chemical conditions in San Francisco Bay, at the Ferry Building, in July, 1923.

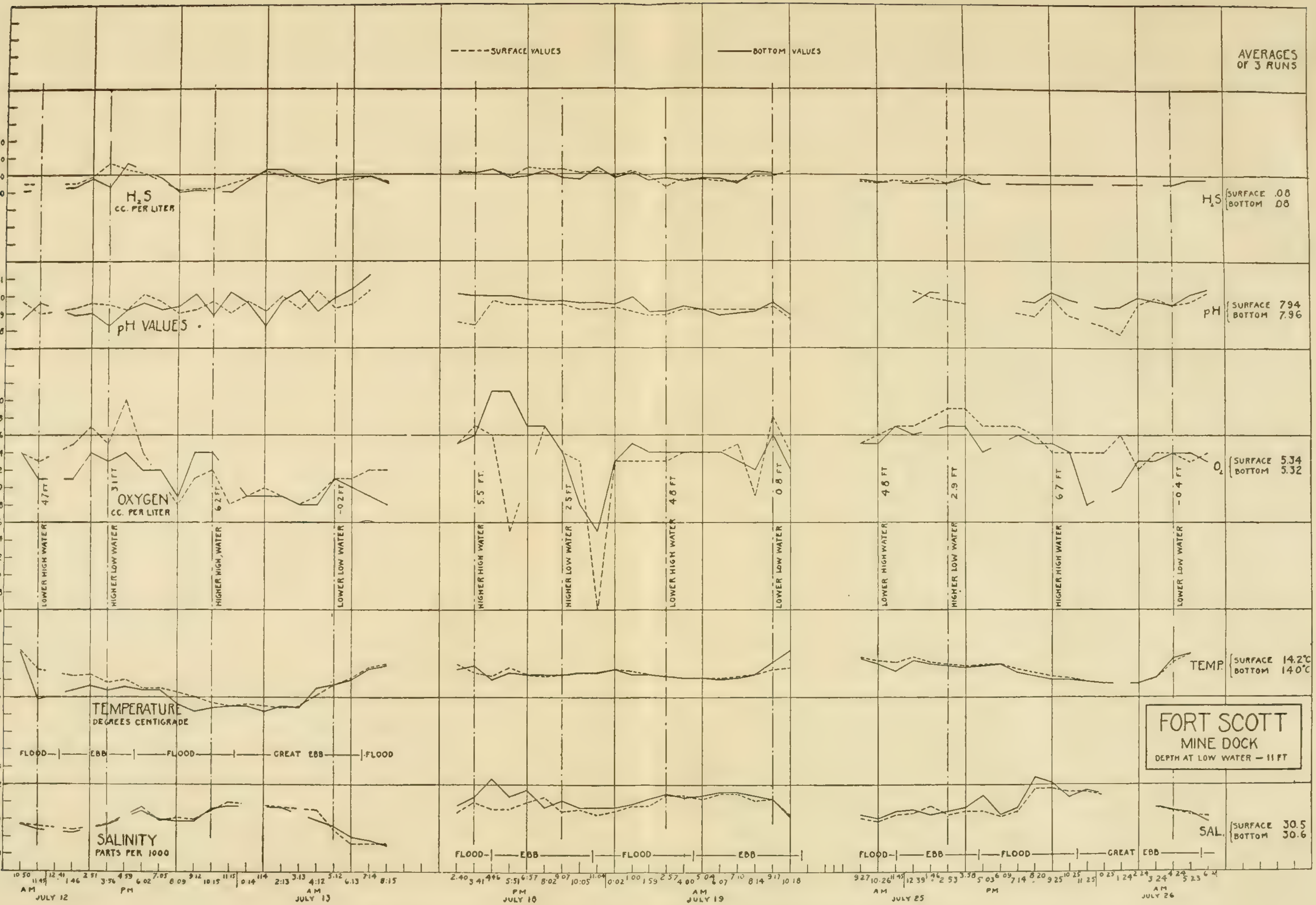

Fig. 105. Graphs of physical and chemical conditions in the Golden Gate, at Fort Scott, in July, 1923.

pH 7.50, at Crockett; the highest was pH 8.16, at the Oakland Mole, thus giving a range of only 0.66 Sörensen unit for the entire bay.

The average values for each condition at each locality are indicated in the graphs. The variations from hour to hour, as shown in the graphs, are decidedly irregular; but in a majority of cases the larger variations are correlated with the ebb and flow of the tide. This correlation is obvious at Crockett and Dumbarton, and is shown, though in less degree, at the Ferry Building. These three stations border on strong tidal currents of well-marked direction. On the other hand, at the Oakland Mole and at the Fort Scott Mine Dock, both of which localities stand rather in the backwash of the major tidal currents, only a slight degree of correlation between the condition of the water and the ebb and flow of the tide is to be observed.

A study of the graphs will show that in general the dissolved oxygen and pH values tend to vary together, and that they bear an inverse relation to the amount of dissolved hydrogen sulfide. Thus it will be noted that from the first to the last run at all stations there is a general upward trend of the pH values with a corresponding upward trend of the amount of dissolved oxygen, and a downward trend of the hydrogen sulfide. This relation is so variable, however, that no one factor can be regarded as a satisfactory index to the others.

It is to be concluded from this study that the high oxygen content and low hydrogen sulfide content of the waters of San Francisco Bay as a whole present conditions favorable to the growth and reproduction of *Teredo* and its allies insofar as these factors are concerned, while it is believed further that the narrow range of Sörensen values observed would have little or no effect on so hardy and adaptable a group of organisms. For so large a body of estuarine water, San Francisco Bay presents a surprisingly uniform environment. Salinity and temperature are the most important variables; their effects are discussed elsewhere, in this and the following chapter. The other factors considered appear to play a minor role as regards their effect on the distribution of marine borers, unless it be in the immediate vicinity of sources of considerable pollution by sewage or industrial wastes (see below).

Effects of Sewage Contamination

It has been claimed that pollution by sewage and industrial wastes may be a factor of some importance in the prevention of damage by marine borers in harbors where such pollution is great. The data set forth above indicate that sewage contamination is a factor of little importance in its effect on the condition of the water of San Francsico Bay. In order to throw further light on this point, it was decided to make a special investigation of conditions near the mouth of a sewer, to determine the effect of pollution on the water immediately proximal to the sewer outlet, and the rapidity with which such effect is dissipated with distance.

The locality selected for this purpose was the Channel Street canal, San Francisco. This canal, about 1200 yards long and 50 yards wide, joins the bay in the so-called "China Basin," near pier 42. The only flow of water is that produced by the rise and fall of the tide. At its upper end the canal receives the discharge of the Channel Street sewer. This sewer is designed primarily for storm water overflows, but is temporarily carrying some human sewage, and has in the past carried a great deal more.

Water samples were taken at low water slack on August 15, 1923, and at high water slack on the following day, at each of three localities along the canal: one at the upper end, about 100 yards from the mouth of the sewer (station A); one near the lower end, about 100 yards from the bay (station B); and one at pier 42, about 50

yards outside the entrance to the canal (station C). As the depth of the water at the upper end of the canal was only about 1 foot at low tide, and about 6 feet at high tide, one sample was considered sufficiently representative of both surface and bottom conditions. At stations B and C, where the depths at low tide were, respectively, 30 and 40 feet, separate surface and bottom samples were taken. The results are shown in the accompanying table:

CONDITIONS AT THE MOUTH OF THE CHANNEL STREET SEWER

		Salinity parts per 1000		Dissolved oxygen c.c. per liter		Dissolved** hydrogen sulfide c.c. per liter		Hydrogen-ion concentration pH	
		Low water	High water	Low water	High water	Low water	High water	Low water	High water
Station A		25.77	30.39	(1.60)*	2.61	12.09	0.08	7.09	7.42
Station B	Surface	30.23	30.68	3.75	3.69	0.08	0.10	7.50	7.48
	Bottom	30.73	31.29	4.38	6.17	0.08	0.08	7.50	7.67
Station C	Surface	30.53	30.53	6.14	5.69	0.10	0.10	7.61	7.77
	Bottom	30.61	31.78	6.07	6.35	0.10	0.10	7.74	7.76

*Sample taken at low water slack, August 17, 1923. **Iodometric method.

These data show a very low content of dissolved oxygen at station A, nearest the sewer outlet, and a correspondingly low Sörensen value. The value for hydrogen sulfide is extraordinarily high at low tide, owing probably to the presence of a great deal of organic matter in suspension, in addition to the actual amount of hydrogen sulfide in solution. The lowered salinity, as compared with stations B and C, is of course due to dilution with sewage water.

At station B the dissolved oxygen and pH values are still notably low, though higher than at station A. The dissolved hydrogen sulfide has dropped to a nearly negligible figure. The fact that the surface values for dissolved oxygen are lower than the bottom values, which is contrary to the general rule, indicates that the sewage contaminated water tends to flow out on top of the more saline bay water. This is also shown in the pH values at high tide.

At station C, fifty yards outside the entrance to the canal, the chemical effects of pollution have almost or altogether disappeared. The salinity and dissolved oxygen values are higher, and the hydrogen sulfide values lower, than is the average for this part of the bay (judging by our results at the Ferry Building; see fig. 104). The Sörensen values are lower than the average, but this may only doubtfully be attributed to the effect of pollution.

The conditions prevailing at station B indicate approximately the limit of pollution that the marine borers are able to survive. Although *Teredo navalis* has not been found at this locality, *Bankia setacea* is known to occur here, and to have done considerable damage in the spring of 1922 to temporary piling driven during the construction of the new China Basin Terminal. No *Limnoria* were found at that time; and it is believed that neither *Bankia* nor *Limnoria* are able to survive much farther up the channel than this point.

The foregoing data indicate that the effect of sewage in San Francisco Bay is quickly dissipated by the strong tidal currents prevailing; sewage pollution cannot be expected to afford protection from borers except actually at the mouths of large sewers.

CHAPTER XVII

THE BIOLOGY OF TEREDO NAVALIS (*Continued*)

Variability and Environment

The shell and pallets of *Teredo* are structures which are subject to a wide range of variation, which, as mentioned in an earlier chapter, has been a cause of much confusion in the classification of the group. It is of interest, therefore, to consider the range of such variations in the case of *Teredo navalis* and the extent to which they may be referred to known conditions of the environment. Such a study in the case of one species sheds considerable light on the general problem of the taxonomy of this group.

Variations in the Shell

There is scarcely a detail of the structure of a *Teredo* shell which does not exhibit variability. The outlines of the shell and the relations of the various parts to each other are frequently markedly dissimilar in different specimens. This is particularly true with reference to the auricle, which may be reduced or very prominent, rounded or quadrate, or elongate and reflected; its position varies between posterior and postero-dorsal. Other marked variables are the prominence of the ridges on the anterior and median lobes and the width of the spacing between them, details of the serrations on these ridges, width of the anterior median denticulated area, size of the angle formed at the junction of anterior and median lobes, degree of convexity of the shell, and thickness and color of the periostracum. On the interior of the shell, considerable variation occurs in the relative length and breadth of the apophysis, and in the width of the shelf produced by the slight overlapping of the inner edge of the auricle upon the median portion.

To treat in detail of all the deviations observed in these studies would be a practical impossibility, as well as inconsistent with our limited knowledge of the conditions which occasion them. We have accordingly confined attention to those variations which are at once the most salient and the most easily described or expressed in terms of numerical coefficients. Such are the variations occurring in numbers of ridges, in length of auricle, in certain details of surface sculpture, and in color. These will be considered in the following pages in relation to what seem to be their principal environmental antecedents.

In order that any effect of environment in producing variation might be observed in its maximal expression, we selected for this study specimens of *Teredo* from localities most distinctly characterized by the physical differences we have described. Specimens from the upper bay have been taken principally from the region of Carquinez Strait, those representing the middle bay from Goat Island and from the Southern Pacific and Western Pacific moles, and those considered typical of the lower bay have been collected at Dumbarton.

Variation in Number of Ridges

It was observed in the course of a study of the rate of growth of the shell (see p. 289), that shells from Goat Island show a slight but consistent advantage in number of ridges over shells of the same age from Crockett. The significance of this was not immediately evident. In order to let further light on the matter, it was decided to

count on several series of shells *the number of ridges per millimeter* or an arbitrarily chosen part, in order to determine whether or not there is actually *a greater number of ridges per unit area* on the shells from the middle bay. The portion of the shell chosen was the first millimeter of the anterior median denticulated area, approximately in a line with the lower edge of the anterior lobe, but definitely at right angles to the ridges. The following curves (fig. 106) are based on 50 shells from each of three localities.

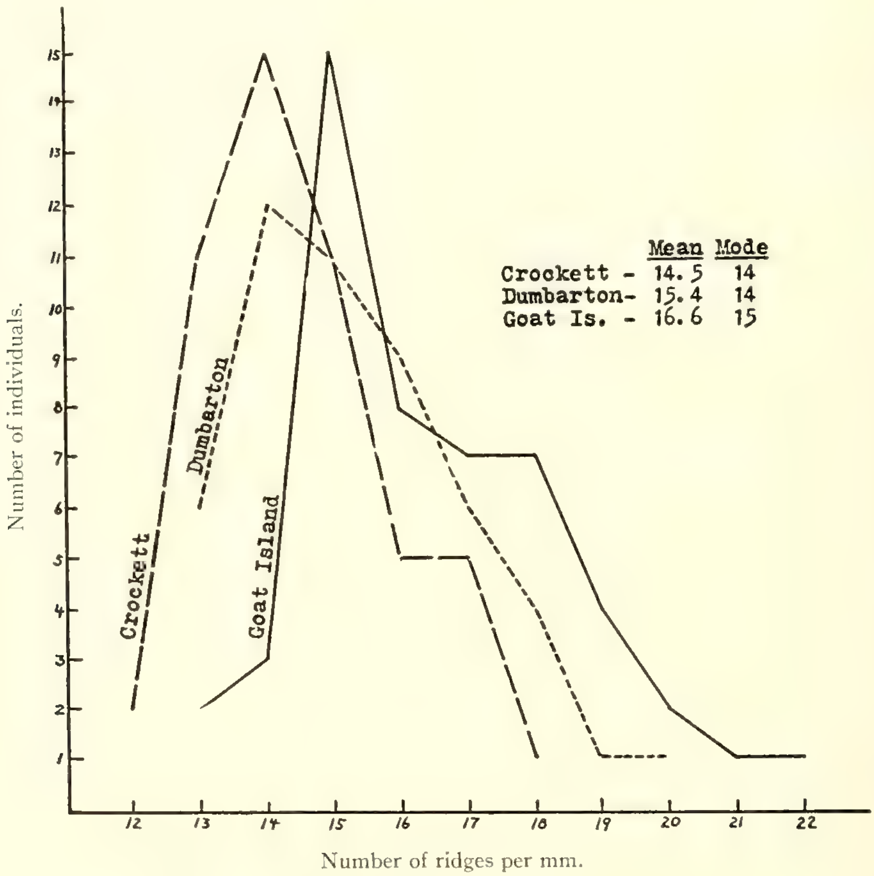

Fig. 106. Graph showing number of ridges per mm. on shell of *Teredo* from three stations.

These curves appear to indicate a very definite correlation between environmental conditions and the number of ridges per unit area on the shell, the greatest number of ridges being found on shells from the middle bay, and the least number on shells from the upper bay, while those from the lower bay stand intermediate between them. The exact reason for this correlation is not entirely clear. We would suggest that it lies both in the absolute differences in temperature and salinity and in the range of such differences.

That environmental conditions play a prominent part in determining the deposition of ridges there can be no doubt. We are often able to read in the sculpture of a series of shells from a given locality the history of some definite alteration in the life conditions, which has left its mark on a number of shells. As an example of this, note in fig. 107 the unusually wide interspace by which the newest ridge is separated

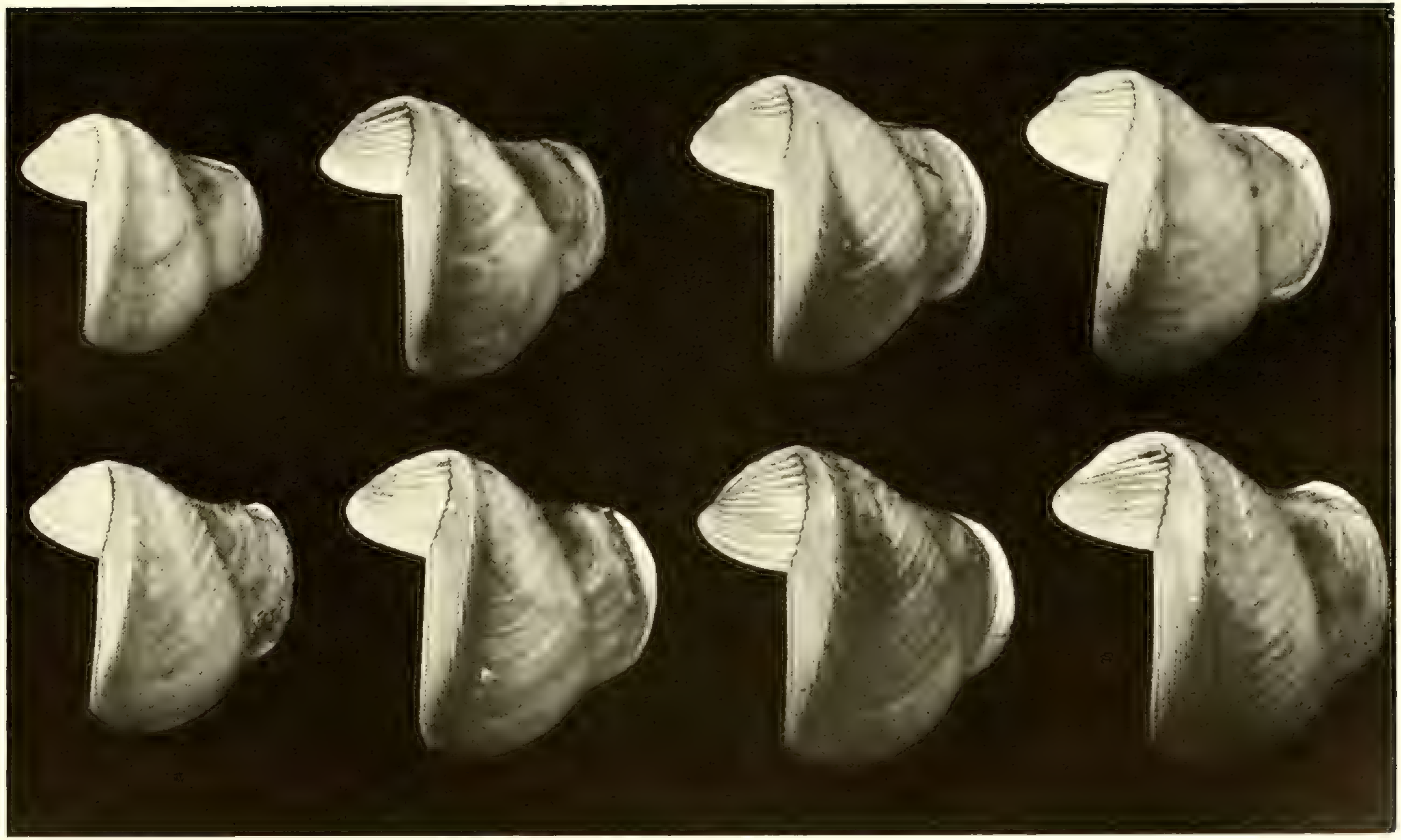

Fig. 107

Series of shells of *Teredo navalis* from Crockett, showing effect of environment on growth of ridges. Note on each shell the unusual width of the interspace separating the newest ridge (left) from previous ridges. ×9.

from its neighbors, this same condition occurring in a number of shells taken at the same time and place.

With the foregoing facts in mind, we naturally infer that the combination of conditions occurring in the upper bay tends to produce certain changes in the physiological cycle of ridge deposition, the net result of which is a smaller number of ridges per unit area of the shell than we find to be the case under the conditions prevailing in the middle and the lower bay. This corresponds with the results of table 43 and 44, which indicate *a smaller number of ridges per unit of time* for shells from the upper bay. That is, in the Carquinez Strait region, *Teredo* deposits ridges farther apart and at wider intervals of time than at stations down the bay.

A further note of interest on the effect on *Teredo* of lowered salinity and fluctuating temperature is the difference to be observed between shells at different levels of the same pile in the upper bay. This is well brought out in fig. 108, where we have compared a series of shells taken at Crockett from near the mud line of a pile (depth 20 feet) with a series from near the top of the same pile, taken at about low tide level. Our hydrographic data show that the differences between surface and bottom salinities at this point, owing to the greater specific gravity of the more saline water, may at times be as great as 6 parts per 1000 (Kofoid and Miller, 1922, p. 81; see also fig. 100). We know further that in this location conditions sometimes prove lethal to *Teredo* near the top of a pile, while permitting it to survive lower down. In other words, the surface conditions here are very close to the critical point which determines the life or death of the animal.

The shells of *Teredo* occurring in this region of stress at the upper end of the pile are very notably dwarfed as compared with those from a greater depth. Furthermore, they have fewer ridges, and the interspaces separating these are considerably wider (fig. 108, *1*, *2* and *3*). These facts are entirely consistent with our previous conclusions regarding the effect of lowered salinity and fluctuating conditions, being merely an exaggeration of the differences found between shells from Crockett and Goat Island.

It is to be remarked also that shells from near the surface at Crockett are very similar to shells from near the bottom at Port Costa and Martinez, points farther up the bay, where *Teredo* leads a precarious existence and rarely survives the fresh-water period of winter floods.

Elsewhere in the bay the effect of depth has not been taken into consideration, owing to a paucity of material from near the tide levels. A few specimens that we have from the upper part of a pile in the middle bay are not observably different from those taken at greater depths. Conditions at surface and bottom are much more uniform in the middle and the lower bay, and any effect of depth is probably so slight as to be negligible.

Variation in the Auricle

Inasmuch as the variations which occur in the posterior lobe of the shell are rather obvious to the eye but extremely difficult adequately to describe, considerable care has been given to the preparation of figures 109 and 112 (*1*), in order that they may illustrate as accurately as possible the range of the differences we have observed.

The position of the auricle, we have noted above, varies between posterior and postero-dorsal. It was at first thought that this might have some definite significance with relation to the effect of environmental factors; but further study has indicated that the position of this lobe of the shell is in considerable degree determined by the age of the specimen. In younger shells the auricle is normally postero-dorsal; but as it grows by further accretions backward and ventrally, it is *resorbed at the dorsal edge*,

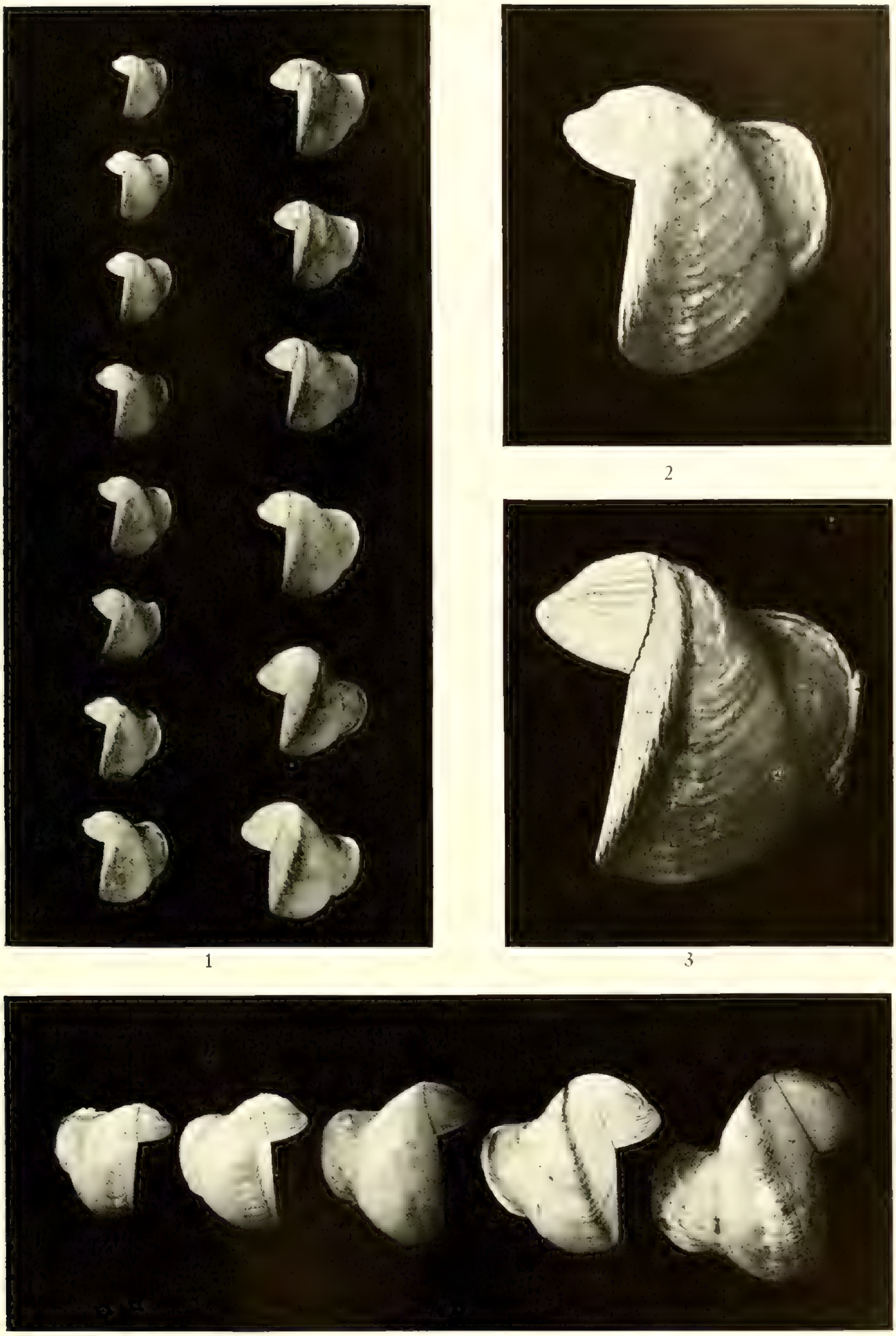

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Fig. 108

1. Comparison of series of shells from near the surface (left) and near the bottom (right) at Crockett. × 2½.

2. Typical shell from near surface at Crockett. × 10.

3. Typical shell from near bottom at Crockett. × 10.

4. Series of shells from Crockett of progressively greater age from left to right, showing change in relative position of auricle through resorption of its dorsal edge with growth. × 4.

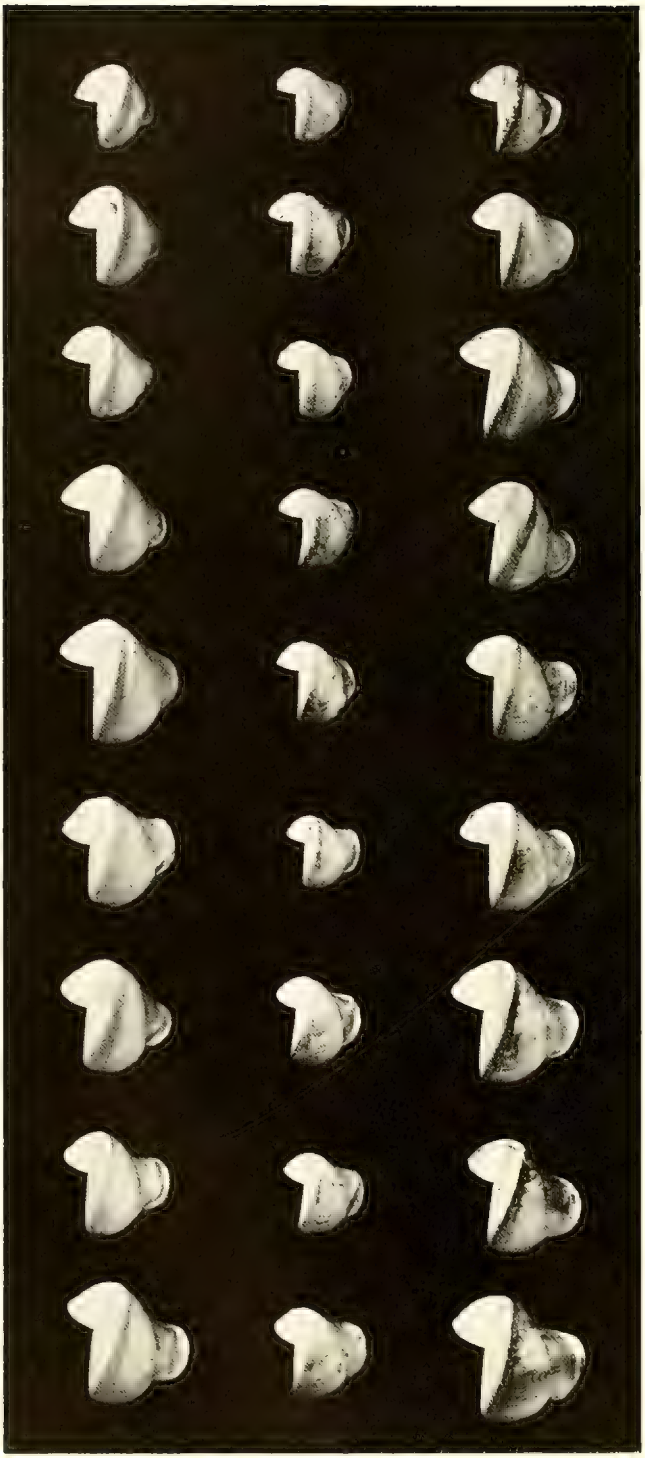

Fig. 109

Comparison of series of shells from Goat Island (left), Dumbarton (center), and Crockett (right), illustrating range of variation at each of these points. $\times$ 2.

Differences in absolute size may be disregarded, as in this case no selection has been made for age.

so that its position with reference to the median part of the shell becomes continually more definitely posterior. This is strikingly illustrated in figure 108, *4*.

With regard to the degree to which the auricle is reflected outward at its posterior edge, a condition which becomes more exaggerated in the older shells, it is sufficient to remark that this is an adaptation to prevent its cutting into the viscera with the rocking movement of the shell which accompanies boring; naturally this condition becomes more pronounced in those shells having the longer auricles.

Shells from the upper bay tended in general to have more prominent auricles than shells from the middle and the lower bay. We undertook, accordingly, to get a definite numerical expression of the degree of this difference. The greatest length of the auricle (measured outside, from the depression which marks its junction with the middle lobe to its posterior edge) was divided by the length of the middle lobe, as measured on a line taken from the angle between anterior and middle, perpendicular to the forward margin of the middle (fig. 110). The resulting quotient was taken as the index of the relation of the auricle to the middle lobe. These indices were then tabulated and used as the basis of a graphic representation of the range of the differences in question.

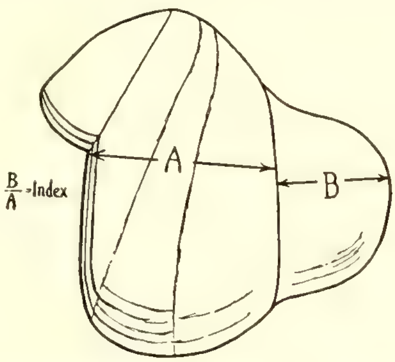

Fig. 110. Diagram of *Teredo* shell, showing method of obtaining index of auricle.

The length of the middle lobe was taken as a constant somewhat arbitrarily, not because it does not vary, but for convenience, and because it was deemed a safer constant than, for example, the entire length of the shell, which would include the possibility of an independent variable in the anterior lobe.

We would mention further that measurements based on the *length* of the auricle give an inadequate representation of the actual range of variation encountered; variation occurs, also, as we have previously stated, in *breadth* and in *shape* (fig. 109); but it is difficult, for obvious reasons, to reduce these factors to a numerical expression. We have for practical purposes considered simply the *prominence* of the auricle, and of this the measured length gives us a fair indication.

The following graph (fig. 111) is based upon 100 shells from each of the three localities selected.

In analyzing these curves, we observe first a constant and rather marked difference between shells from Goat Island and those from Crockett, a difference which is expressed alike in the extremes, the means, and the modes. The shells from the upper bay have a definitely and consistently larger auricle than those from the middle bay. The shells from Dumbarton, as we should have anticipated from our analysis of environmental conditions at that place, stand intermediate between those from the upper and the middle bay. While all three of our curves manifest certain irregularities, owing doubtless to the limited number of shells considered, at seven points

out of a possible eleven the curve representing shells from the lower bay falls between the other two.

The most salient feature of this graph is the closeness with which it agrees with the graph representing the number of ridges per millimeter of the shells from the same three localities (fig. 106). While the relation is indeed an inverse one, it indicates none the less the consistent action of environment in producing variation. In other words, we have studied these groups of shells from two entirely different points of approach, and have arrived in each case at the same conclusion, namely, that the three different types of environment have produced three rather distinct types of variation in the shell of *Teredo*, and that in each case the intermediate environment (the lower bay) has produced a type intermediate between those of the middle and the upper bay, representing the extremes of environment.

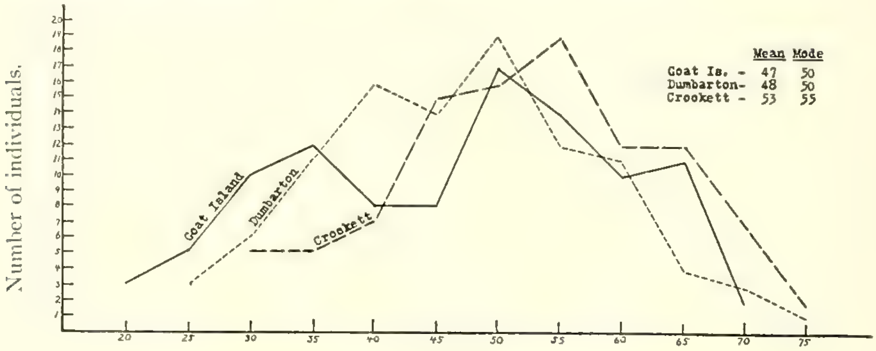

Fig. 111. Graph representing index of auricle of shell of *Teredo* at three different stations.

Variation in Surface Sculpture

Shells from the upper bay are generally more irregularly sculptured and rugose than those from other portions of the bay. They are less transparent and lustrous; the periostracum is thicker and more opaque, and considerably roughened across the middle median area. The lines of growth are more prominent, indicating greater lapses in the progress of growth than occur under the more constant conditions of the middle bay.

It has already been shown that the denticulated ridges are less numerous and less closely spaced on shells from the upper bay than on those from the middle and lower bay. A microscopic study shows that the differences are carried even to the details of the denticles on the ridges. On the shells from the upper bay, with their fewer and more widely spaced ridges, these denticles are more individuated and sharply outlined, having a distinctly serrate appearance (fig. 112, *4*). Shells from the middle bay, on the other hand, have more close-set and less sharply delineated denticles, which under the low power of the microscope, present a beadlike appearance, very different from that just described (fig. 112, *2*). Here once more we find that shells from the lower bay occupy a position intermediate between the other two types (fig. 112, *3*), with a tendency to resemble more nearly the form from Goat Island.

Variation in Color

The shells from Crockett (see fig. 109) are very distinctly more pigmented than those of either of the other series. This is true of shells from the upper bay generally; we have found it to be the case almost without exception in shells from Mare Island,

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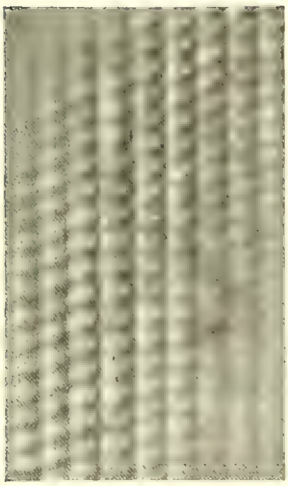

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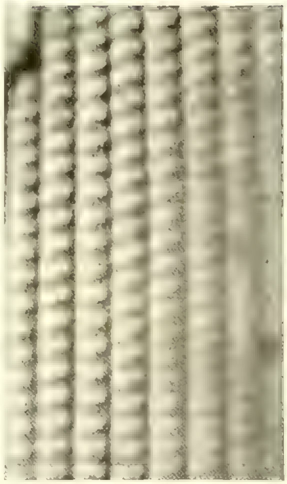

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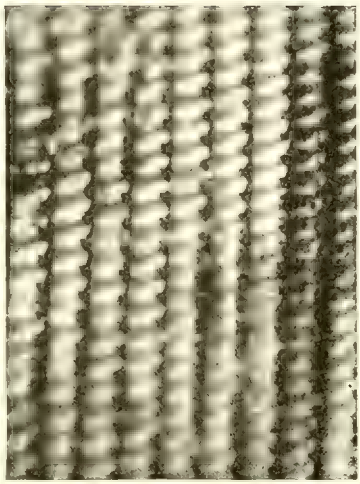

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Fig. 112

1. Comparison of extreme variates of each of the series shown in fig. 109; Goat Island (left), Dumbarton (center), and Crockett (right). $\times$ 5.

2. Details of denticulation of a portion of the anterior median area of a shell from Goat Island. $\times$75.

3. The same, from Dumbarton.

4. The same, from Crockett.

5. Shells from stagnant aquarium, discolored black by action of sulphur bacteria. $\times$4.

6. Head of *Teredo*, with body and shell colored blue as a result of working in redwood in vicinity of an iron nail. $\times$ 4.

Crockett, Port Costa, and Martinez, as compared with shells from Goat Island, Angel Island, Oakland Harbor, and the San Francisco waterfront.

Coloration when present ordinarily manifests itself chiefly in a fairly broad brownish stripe from dorsal to ventral across the middle median portion. This stripe varies in color from a pale brownish yellow through varying shades of brown, often warmly tinged with red, to heavy sepia; the color nearly always tends to fade out toward the dorsal and ventral margins of the shell. In addition to this median stripe we often find, more especially in shells from the upper bay, a roseate or occasionally brownish color suffused over the denticulated area (anterior median); in the more heavily pigmented shells a distinctly reddish or brownish patch occurs on the auricle.

As regards the absolute differences of coloration in shells from the upper and the middle bay, it is difficult to make any statement more definite than that the former manifest color in maximal, the latter in minimal, amount. Shells from the upper bay are characteristically marked with reddish or brownish color, while those from the middle bay are lighter and more translucent, and often entirely white. The Dumbarton shells more nearly resemble, in this respect, those from the middle bay.

With our present limited knowledge of the physiology of *Teredo*, the basis of these differences in color is difficult to determine. The color lies entirely in the periostracum, which may be scraped off, leaving the shell perfectly white. This would suggest that the thickness of the periostracum is at least a factor in producing depth of color. It has been stated above that the shells from the upper bay exhibit a thicker and rougher epidermis; it is natural therefore that these shells should have the deepest color, while those from the lower bay would be lighter, owing to the white prismatic layer showing through the thinner epidermis.

That coloration is, however, in considerable measure directly dependent on immediate factors of environment, independent of the thickness of the periostracum, becomes evident from certain types of what we may term "accidental" coloration that have been occasionally observed.

In two different instances we have found that a nail driven into a redwood timber below water line has produced an area of black discoloration (ferric tannate) through the action on the iron of the tannic acid in the wood. Teredos were working successfully in this discolored area, but their bodies and shells were deeply stained with blue (fig. 112,*6*). Teredos working elsewhere in the same piece of wood were not so colored.

In a number of instances we have found that the shells of *Teredo* left in stagnant water in our aquaria were colored almost entirely black by the action of sulphur bacteria (fig. 112, *5*). This must have been due to some physiological cause, as the shells of dead teredos under the same circumstances were not discolored.

Variations in the Pallets

We have shown in figure 61, series of pallets from three localities in San Francisco Bay, namely, Crockett, Dumbarton and Goat Island. In each of these series, the pallet at the extreme left of the illustration is regarded as approaching the type of *navalis*, as figured by Jeffreys (1869) (see fig. 69). The other specimens in the series represent departures in greater or less degree from the type. The smaller size of the Dumbarton material is not regarded as significant; our specimens from this locality were secured from timbers exposed only a few months, whereas specimens from the other two localities were taken when older. But by the time the animal has reached an age of one month the pallets have assumed normal proportions, and, so far as our observations go, no changes ensue thereafter as a result of growth alone.

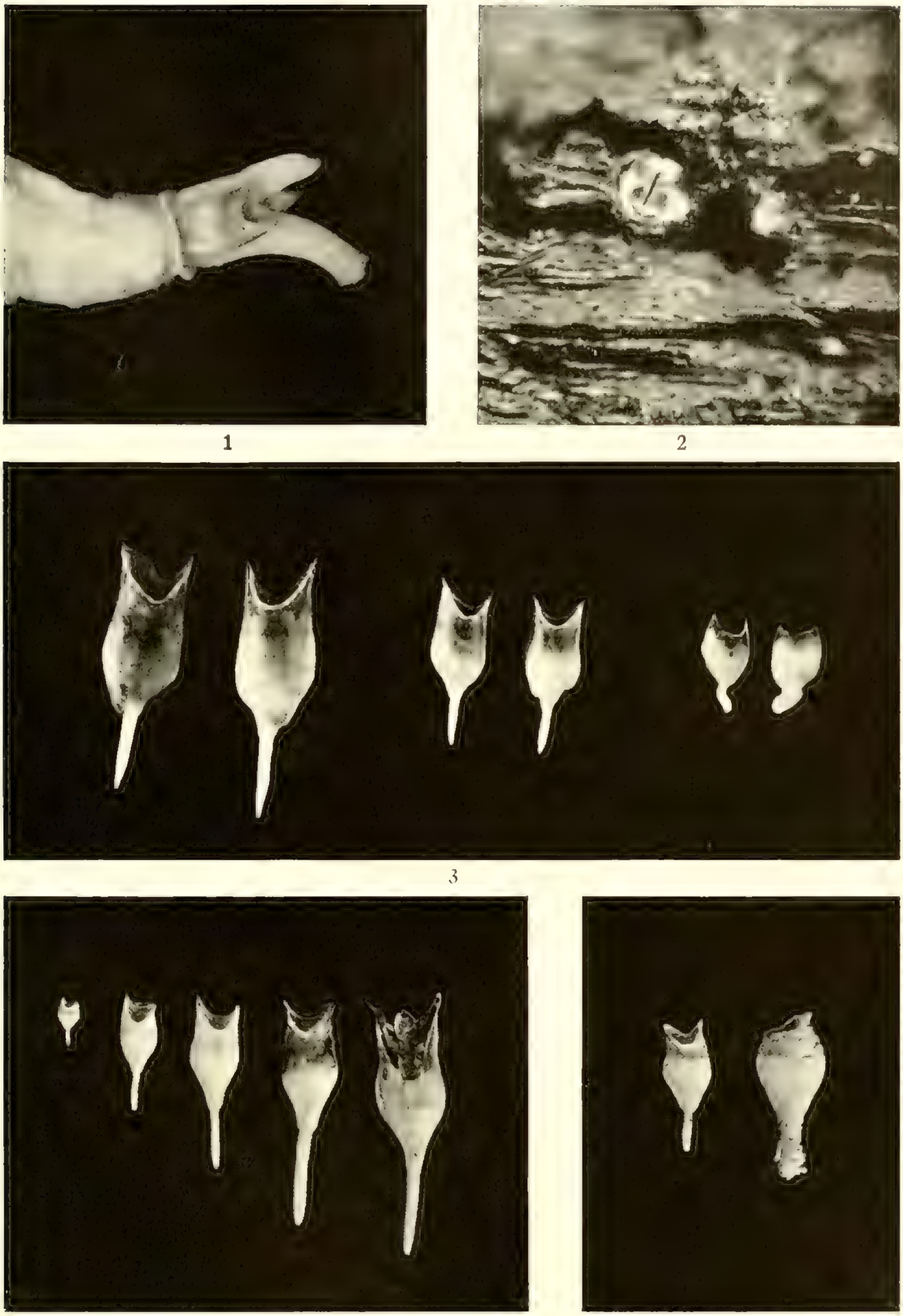


Fig. 113

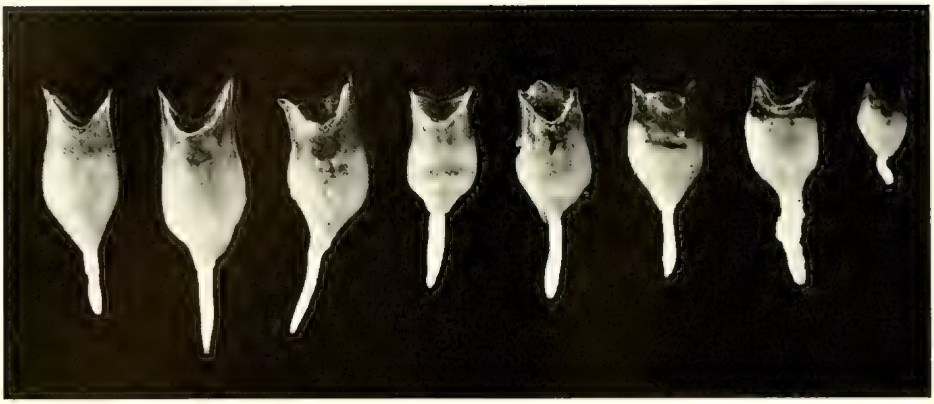
1. Siphonal end of *Teredo navalis*, showing position of pallets. × 5.

2. Pallets in position, closing entrance to burrow. The dark area at the right is the opening to the burrow of an older, retracted specimen. × 10.

3. Pallets arranged in pairs, illustrating variation in two members of the same pair. × 5.

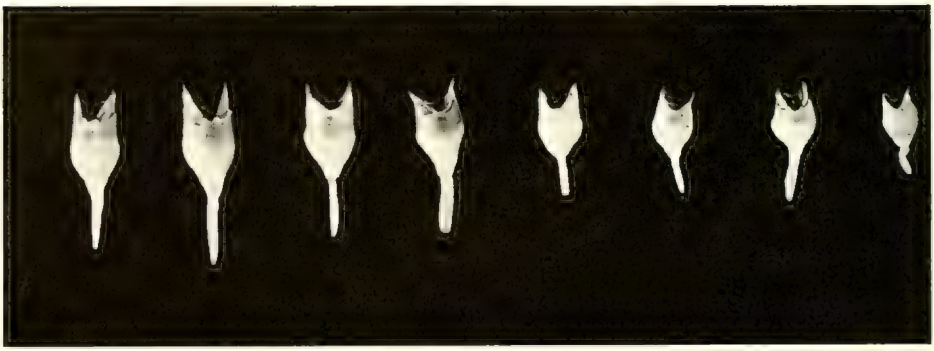
4. Series of pallets from the Oakland Harbor Light Station, representing ages of approximately two weeks (?), one month, two months, three months, and four months, respectively.

5. Comparison of a normal and nearly typical pallet from Goat Island with an older one from the same location, showing maximal effect of age and erosion.



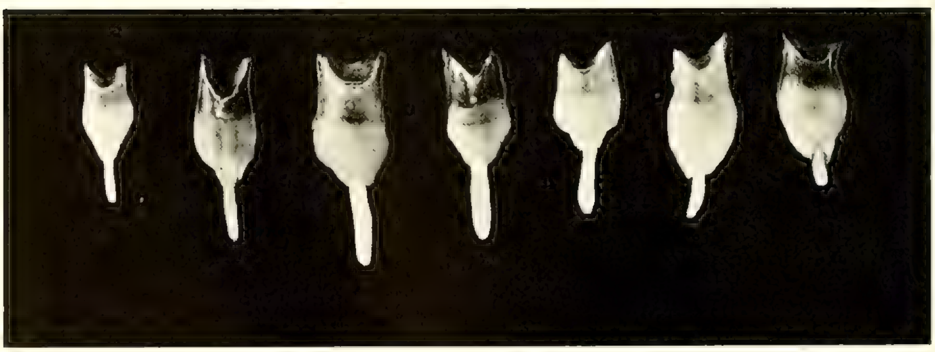
a *b* *c* *d* *e* *f* *g* *h*

1



a *b* *c* *d* *e* *f* *g* *h*

2



a *b* *c* *d* *e* *f* *g*

3

Fig. 114

Variation in pallets of *Teredo navalis*

1. Series of pallets selected to illustrate variation at Crockett, San Francisco Bay.
2. Series of pallets selected to illustrate variation at Dumbarton, San Francisco Bay.
3. Series of pallets selected to illustrate variation at Goat Island, San Francisco Bay.

All figures × 5.

A small series of pallets selected for age is shown in figure 113, *4*. The factor of individual variation could not be entirely eliminated even in this limited group; but it is rather evident that such changes as occur after the first month are due primarily to effects of wear and a gradual darkening of the chitinous tip, which generally becomes more pronounced in the older pallets. Indeed, the pallet estimated to be one month old more nearly approaches what we consider the type of *navalis* than do the others in this series.

In studying variation in the pallets, it is important that physiological factors should be separated so far as possible from purely physical ones. Of the latter there are those already mentioned of accident and erosion. The pallets are, from the nature of their function, much exposed to unfavorable circumstances. In times of stress they form the barrier against undesirable and often lethal conditions. They are much subject to wear from being frequently thrust into the constricted end of the burrow. While in such position they may be eroded by organic acids present in the water or the wood. If a foreign object, a piece of floating driftwood, for example, comes violently into contact with the surface of a timber in which teredos occur, the pallets are likely to be broken.

In figure 113, *4*, it will be seen that even a pallet four months old may show very decidedly the effects of wear. In figure 113, *5*, we have compared a normal and rather typical pallet from Goat Island with an older pallet from the same locality which illustrates the maximal effect of age and erosion, the original form of the distal portion of the blade being entirely lost. The secondary calcareous accretions about the stalk may be pathological; similar accretions have been noted in other cases, as in figure 114, *1*, *g*, but are infrequent.

The pallets may also be secondarily modified by the nature of the burrow. If the course of the burrow deviates suddenly near the opening, the pallets will tend to be asymmetrical, with the stalk curved and inserted at one side of the median line, as in 1*c*, figure 114. If the burrow be straight for some little distance from the surface, expanding gradually and regularly, the pallets will usually be well formed, elongate, and tapering (fig. 114, *2 b*). If the burrow expands suddenly, owing to an unusually rapid growth of the animal, or if the opening becomes enlarged, as may easily occur in soft wood, the pallets are likely to be broad and blunt in appearance (fig. 114, *3 e*). In other words, if they are to perform their function aright, *the pallets must fit the burrow;* hence they will be influenced by the factors determining the nature of the latter, such as rapidity of the growth of the borer, hardness of the wood penetrated, and the degree of crowding, which often determines the course of the burrow.

Excluding the foregoing factors, which may be spoken of as *adventitious*, we find yet a number of variations which we may term *physiological*, in that they are indirectly rather than directly produced. These may be separated into two types, which for convenience we shall term *individual* and *environmental*, the former considered to be produced by obscure causes bound up in the physiology of the individual organism, the latter affording some evidence of correlation with conditions of the environment.

As an illustration of individual variation, we would call attention to differences which frequently appear between two pallets of the same pair. Examples of this are shown in figure 113, *3*. The differences between the members of each of the three pairs of pallets figured are so marked that they would not have been suspected of belonging to the same pair, had we not actually removed them from the animals. Variations of this sort cannot of course be attributed to factors in the environment (exclusive of those of an adventitious nature), which would be expected to operate alike on the two members of each pair; rather do they represent some unknown factor

of the biochemical or other aspect of the organization of the animal which tends to asymmetry.

We have found in our study of pallets that the range of this type of variation is so great as to render it extremely difficult to recognize variations resulting from ecological factors. It has been noted, however, that pallets from the upper bay tend to have a heavier periostracum than those from the middle and lower bay, which corresponds with our observation concerning the periostracum of the shell (p. 278), which was found to be thicker and rougher in the case of specimens from the upper bay. It may be stated also, as a fact of general observation, that the chitinous tips of the pallets tend to be darker in color in specimens from the upper bay than in those taken elsewhere. This is not always true in individual cases, as will be seen by reference to figure 114; the tips of pallets *3b*, *3d*, and *3g*, in the Goat Island series are almost as dark as the darkest of the Crockett pallets (*1g*); but the proportion of pallets with a notably dark distal portion is greater among the pallets from the upper bay.

It should be mentioned in this connection, however, that pallets taken near the mud line of a pile, or from waters containing much decaying organic matter, are likely to be much stained, as was observed in the shells (p. 278). It is necessary, therefore, to be cautious in interpreting such data.

Systematic Bearing of Variations

The data presented in the foregoing pages appear to demonstrate that certain variations occurring in the shell of *Teredo navalis* in San Francisco Bay have a definite relation to corresponding ecological conditions. This inevitably suggests some discussion of the systematic treatment to be accorded such environmental forms.

The type of variate occurring in the upper bay has been described by Bartsch (1921) as *Teredo beachi*, n. sp., San Pablo Bay being designated as the type locality. The diagnostic characters which distinguish this form from the type of *Teredo navalis* are not definitely stated. But we note in the description mention of a "strong posterior auricle . . . umbones and a streak in the middle median portion . . . rose colored . . . dental ridges . . . very strongly denticulated . . . strong auricle . . . marked by rough lines of growth . . . center of the median portion is marked by a roughened area . . . auricle is marked by strong, curved lines of growth . . ." etc. The emphasis on the large auricle, color, strong denticulation, median roughened area, and prominent lines of growth, as well as the type locality given, identify this teredo as the environmental form which we have considered typical of the upper bay. The wide variation we have described in these characters obviously precludes such variants from specific rank. The question remains as to whether *beachi* should be retained as a sub-species, or included in the synonymy of *navalis*. In case of the former alternative, a subspecies would have likewise to be established for the form from the lower bay and perhaps, also, as further study might show, for each of several intermediate environmental forms at other localities, the Goat Island form being considered typical. It might even be necessary in some cases to establish subspecies for teredos from the top and the bottom of the same pile.

It will be recalled that the localities from which shells were taken for this study were chosen as representing the *extremes* of environment in which *Teredo* occurs in San Francisco Bay. Also, in attempting to establish the effect of environmental conditions in producing variation, we have naturally and legitimately emphasized the *differences* rather than the *similarities* observed among specimens from the localities in question. We would call attention to the fact that, while the extreme differences

are rather marked, the mean differences among shells even from these specially selected localities are comparatively slight. In many, indeed in most, cases it is impossible to take an isolated unmarked shell and declare from what locality it has come. By referring again to figure 106 it will be seen that shells having from 13 to 18 ridges per millimeter might come from any of the three localities considered, the curves overlapping to this extent. From figure 111 it is evident that the index of the auricle may range from 30 to 70 without indicating the locality from which a shell has come. A similar statement may be made regarding the other points of difference noted among these three environmental races. It is only in the case of the extreme variates that a locality diagnosis can be made on the basis of intrinsic characters of the shell.

Furthermore, as we depart from the extremes of environment, the differences mentioned appear to become more and more obscure, until they are entirely lost, the various races merging with each other at intermediate points. Sufficient material is not available adequately to illustrate this, but a few specimens are at hand from stations between Crockett and Goat Island which indicate at least the trend to such coalescence. From Oleum (see map) we find in 25 shells a variation of from 14 to 20 ridges per millimeter on the anterior median area, and a range of from 28 to 67 in the index of the auricle, thus indicating, with due allowance for meager numbers, a slight departure in both these respects from the shells from Crockett, and a tendency more nearly to resemble shells from Goat Island. The shells from Oleum are also less pigmented and more translucent, and in general appearance give the impression of intermediateness between the brackish water and the salt water types. They differ from the Dumbarton shells in having rather more prominent lines of growth.

A solitary specimen from Pinole in our collection cannot be said to differ appreciably from the specimens from Oleum.

On the other hand, we have from off Point San Pablo and Point Richmond a few immature specimens which closely resemble *Teredo* of similar age from Goat Island.

These data, fragmentary as they are, throw much doubt on the advisability of attaching varietal names to any local groups. The free swimming larvae of *Teredo* are swept about by shifting currents to every portion of the bay, and with every breeding season a new distributional assortment must occur, so that any locality differences which appear in the mature animals must be the immediate result of environmental factors acting separately on each generation. The most conclusive proof of this has come in a very interesting way from what at first appeared to be a discrepancy in our data. It was observed that shells from the region of Carquinez Strait taken in 1920 differed appreciably from those taken in 1921 and subsequently, being distinctly more like the shells typical of the middle bay. For example, 40 shells collected at Crockett in 1920 averaged 15.8 ridges per millimeter on the anterior median portion, as compared with an average of 14.5 for shells collected there in 1921 and later. This proved very puzzling, until it was remembered that the winter of 1919-1920 was a period of unusually scant rainfall and consequently lessened river discharge into the northern arm of the bay, resulting in a protracted period of rather high salinity in this region (Kofoid, 1921, p. 49). With the resumption of normal river discharge in the winter of 1920-1921 the salinity was lowered. This seems to be the explanation of the differences found between shells collected here in 1920 and 1921 respectively.

The winter of 1919-1920 was marked by probably the lowest river discharge since 1863-1864; shells collected during this period were accordingly excluded in preparing the foregoing tables and graphs, as representing a departure from the normal. They

serve to illustrate, however, the degree to which variations in the shell of *Teredo* are immediately dependent on conditions of the environment.

The non-genetic nature of such variations is further indicated by the fact noted above (p. 272) that, under certain conditions, rather marked differences may occur between shells from near the upper and lower ends of the same pile.

There is no reason to believe that variation in *Teredo navalis* is a phenomenon limited to San Francisco Bay. Rather is it a biological factor to be reckoned with wherever the distribution of this species extends. Such being the case, we would urge extreme caution in the recognition of new species in this group until their claims be established on the most incontrovertible evidence. This is especially desirable in view of the facility with which *Teredo navalis* invades estuarine harbors and is therefore subject to variation resulting from the amplitude of environmental conditions.

Breeding Habits of Teredo Navalis

Teredo navalis is an incubatory species, the young organisms being retained in the gills of the female until a rather advanced stage of development is reached. Fertilization of the eggs occurs through the agency of spermatazoa extruded into the water by a male animal, and taken by chance into the mantle cavity of the female with the respiratory current. The fertilized eggs then undergo development in a specialized brood pouch formed in the gills by the fusion of adjacent filaments. During the breeding season the female animals are found normally with the brood pouch distended and packed with minute larvae in various stages of development. The ovaries are at the same time enlarged and filled with unfertilized ova, so that it appears that breeding is continued over a period of weeks, the young escaping from the brood pouch from time to time as they become sufficiently mature.

The number of larvae which one female may produce in a season has been variously estimated at from 500,000 to considerably more than 1,000,000. The old Dutch naturalist Sellius (1733) estimated the number of ova contained in the body of *Teredo navalis* to be 1,874,000. A specimen of medium size sectioned by us was estimated, by counting the ova appearing in section over a given area, to contain 750,000 ova. Another specimen was similarly estimated to contain not less than 1,000,000. These estimates being based on the number of eggs contained in the ovaries at one time, the total number produced by the larger females during a breeding season extending over several weeks or possibly months must be greatly in excess of these figures. The marked development of the ovaries during the reproductive period is illustrated in the photomicrograph, figure 115. In this single cross section somewhat more than 2000 eggs are in evidence.

The immature eggs in the lobules of the ovaries, as seen in this figure, are irregularly pear shaped; but on ripening and prior to fertilization they become spherical. The development of the egg within the brood pouch after fertilization has been described by Quartrefages (1849b) and in somewhat greater detail by Hatscheck (1881). Cleavage is unequal; the three germ layers are very early differentiated; no cavity is formed in gastrulation. The smaller ectodermal cells grow around the larger blastomeres which represent the future entoderm and mesoderm, forming thus a ball of cells with the larger inside. The mouth and later the anus are developed by invagination of the outer layer of ectoderm, and finally the inner entodermal and mesodermal cells become differentiated to form respectively the intestine and the muscular system, and also certain other derivatives. In the meantime the shape of the embryo, which at first was nearly round, has become altered. The preoral region is somewhat broadened and flattened, while the post-oral portion of the body tapers slightly. The whole

embryo becomes covered with cilia, most of which are later lost, although some persist, forming a pre-oral and post-oral ciliated ring and a post-anal ciliated tuft. There is also a tuft of cilia in the center of the flattened area.

At an early stage a *shell-gland* is developed from the ectoderm of the dorsal part of the body, and this soon secretes a thin integument which is the rudiment of the shell. At first the shell is single, but as it begins to extend around the body a median dorsal line appears which separates the shell into two lateral valves; this corresponds to the hinge line of the adult.

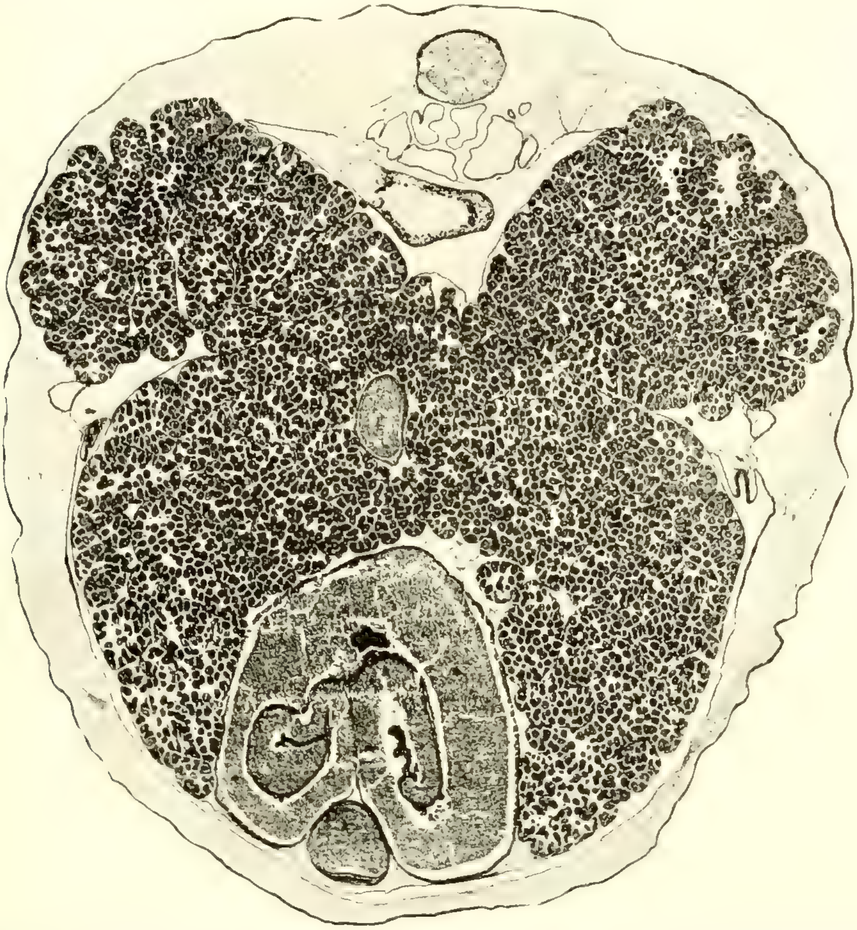


Fig. 115. Photomicrograph of cross section of female *Teredo navalis* in the region of the caecum, showing marked development of the ovaries at the reproductive season. The small dark objects are individual ova.

Even after the shell has grown well around the body, the broad, flat pre-oral portion with its ciliary circlet protrudes from between the valves as a *velum* or swimming organ. The larva is now known as a *veliger*, so named from this characteristic organ, and at this stage it escapes from the brood pouch, is passed out through the anal siphon of the parent, and must henceforth shift for itself.

The velum forms a relatively powerful organ of locomotion, and the swimming movements of the larval teredos as observed in an aquarium are quite vigorous. But such minute organisms must be almost completely at the mercy of tides and currents,

so that their swimming movements probably avail little more than to keep them afloat as they are washed about from place to place.

The length of this free swimming larval period is unknown. Repeated attempts to rear the larvae under aquarium conditions have failed, and attempts to carry the organisms through the larval period in cages covered with silk gauze and suspended in the bay have likewise been unsuccessful. A week is the longest period that any of the larvae have been kept alive, and during this time they showed no inclination to settle on wood introduced for that purpose. Thus it appears that the free-swimming period is longer than one week, and there is some slight evidence that it may be in the neighborhood of a month or even more. In 1921 the earliest veliger larvae were found at Crockett on June 29, whereas the first settlement of larvae on test timbers at this locality was observed on August 8, somewhat more than five weeks later. Such evidence is of extremely doubtful value, however, as the possibilities of overlooking either the first veligers or the first settling larvae are practically infinite.

The breeding season and period of larval settlement in general include the summer and autumn months of the year. Along the north Atlantic coast settlement of the larvae of *Teredo navalis* begins in June (Kindle, 1918) or the early part of July (Nelson, 1922). In San Francisco Bay the season does not begin as early as this except at one locality. The dates of first settlement of larvae at certain localities in San Francisco Bay during three successive years are given in the following table:

TABLE No. 42

DATES OF FIRST SETTLEMENT OF TEREDO LARVAE IN SAN FRANCISCO BAY DURING THREE SUCCESSIVE YEARS

Locality	Date of first settlement		
	1921	1922	1923
Dumbarton	July 20	July 21	July 20
Goat Island	August 15	August 14	....
Crockett	August 8	September 20	September 1
Port Costa	August 23	September 28	....

With reference to the dates of first settlement at Dumbarton correction should be made for the fact that test timbers at this place were examined at monthly intervals only so that the earliest settlement in any year might have occurred at any time during the month preceding the date given. There is some reason to believe that larval settlement may occur here as early as July 1. At the other localities inspections of test timbers were more frequent, and the very early stages of attack were discovered on the dates given. The precise dates are not significant, however. They should be interpreted in a general way as indicating the month and approximate time of the month when larval settlement began.

Thus it appears from the table that settlement of teredo larvae on exposed timbers at Dumbarton begins regularly about a month earlier than at Goat Island. There is nothing in the slight differences in salinity at these two localities to suggest a reason for this difference in dates of settlement of larvae, especially in view of the fact that salinities at both places are always above the minimum salinities that appear favorable to larval settlement in the upper bay. Rather should we attribute the earlier breeding activity at Dumbarton to the fact that the temperature of the water in the southern reaches of the bay rises more rapidly during the early spring and summer

than does that of the middle bay, owing to the effect of atmospheric temperatures on so large an expanse of relatively shallow water.

It appears, however, that in the upper bay salinity rather than temperature is the determining factor influencing reproduction and subsequent settlement of larvae. The delayed date of settlement of larvae at Crockett and Port Costa in 1922 as compared with 1921 seems undoubtedly due to the prolonged period of low salinities incident upon the heavy rainfall of the winter of 1921-1922, the effects of which were manifested in increased river discharge until well into the summer of 1922. In 1921 a mean salinity of 15 parts per 1000 was attained at Crockett on July 6 (see fig. 93) and the salinity ranged above this most of the time subsequently; while in 1922 (see fig. 94) such salinities did not occur until July 29, and prior to July 6 for five months salinities had been, except at a few scattered intervals, below 5 parts per 1000.

We conclude then that in the lower bay the commencement of the breeding season depends on the temperature factor, while in the upper bay the salinity factor is more important. In this connection reference should again be made to the detailed studies of the conditions at selected points on San Francisco Bay, in the month of July, 1923 (figs. 101-105). The data on dissolved gases and hydrogen-ion concentration having already been discussed (p. 265), the discussion here will be limited to salinity and temperature.

The July temperatures at Dumbarton average 20.6° C. for both surface and bottom. This is more than 2° C. higher than the average at the Oakland Mole, 5° C. higher than at the Ferry building, and 6.5° higher than at Fort Point. The average salinity at Dumbarton during this period is higher than at the Oakland Mole, and nearly the same as at the Ferry Building. It appears therefore that salinity may be ruled out as a factor of importance in regard to the reproduction of *Teredo* in the middle and lower bay, while the probability is emphasized that temperature is the deciding factor. The thought further suggests itself that the relative scarcity of *Teredo navalis* along the San Francisco waterfront, and its almost complete absence at Fort Point may be a function of the lower temperature prevailing at these localities.

At Crockett the temperatures are nearly as high as at Dumbarton, averaging 1.5° C. less than at the latter locality during the period in question. It is unlikely that this slight difference in temperature accounts in any considerable degree for the delayed breeding season at Crockett, especially in view of the fact that the temperatures prevailing at Crockett are consistently higher than those of the middle bay, where during 1922 the breeding season began a month earlier than at Crockett.

As the salinity increased considerably between the first and last runs at Crockett (fig. 101), the data for each run should be considered separately. As a majority of the surviving adults are at the lower ends of the piles, and settlement of larvae also is heaviest at the lower levels, the bottom salinities are the most important for our purposes. The surface salinities have been plotted as a matter of interest, to show the range of difference in the conditions at the upper and lower levels of the same piling.

The average bottom salinity during the first run was 15.3, during the second 16.9, and during the third 19.2 parts per 1000, while the minimal bottom salinities were respectively 10.3, 13.1 and 13.8 parts per 1000. Now survival and settlement of larvae may occur in salinities much lower than this, as observed at Antioch in 1920. It appears therefore that the controlling element in the delayed breeding season in the upper bay generally is not inability of the larvae to survive, but failure of the adults to reproduce until favorable conditions of salinity and temperature have prevailed for some length of time. Following the period of winter flood water, which hardly begins to subside before June, the surviving adults apparently require a period of

recuperation before breeding activities are begun. The critical conditions affecting the opening of the breeding season, accordingly, are not those found during the summer, but are a function of the length and severity of the period of stress of the preceding winter.

Regardless of the time at which the breeding season begins, it terminates generally throughout the bay in December. Occasionally a straggling settlement of larvae may continue into the early part of January. Piles driven at Crockett in January, 1920, were found to be attacked by *Teredo* and penetrated to a depth of two inches by May. This indicated conclusively the settlement of larvae within that period. Also on January 7, 1924, a few minute larval punctures were noted on a test timber at Crockett which had not shown any evidence of attack when examined on December 24. These two are the only cases that have indicated any larval settlement whatever after December.

Post-Larval Development

The larval *Teredo*, having found attachment on a suitable piece of timber, begins at once to undergo important changes. The shell becomes rapidly altered and adapted to the function of boring in wood, while at the same time the internal organization of the animal becomes modified in connection with the new mode of life and the change from a diet of minute plankton organisms to a diet consisting for the most part of wood.

It has been objected to the theory we have attempted to establish (Chapter 15) of mechanical boring by means of the shell, that the newly attached larva could not conceivably be able to bury itself in wood by the action of the shell alone, which in the larva is more fragile than paper. As a matter of fact, however, no actual boring is done until after the shell has become in a measure adapted to such work.

The surface of submerged timber is invariably coated with a film of surface debris, composed of silt, diatoms, algae and miscellaneous detritus. The attached teredo larva has at first only to scrape about in this surface debris until it has worked itself in and come in contact with the surface of the wood. This much is readily accomplished by the larval shell and foot, but further progress must await the development of toothed ridges on the shell. We have never seen any larvae even partly imbedded in the wood which had not developed one or more series of such ridges. So rapid is the addition of ridges at this critical period in the life of the organism that before it has buried itself from view at least a half-dozen ridges have been added, the shell in the meantime having very nearly assumed the form it presents in the adult.

The method by which the shell becomes modified from the simple protective covering of the pelagic larva to the specialized boring tool of the adult is extremely interesting. Growth of new ridges does not occur evenly around the margins of the larval shell, but occurs most rapidly at the antero-ventral margin. Thus the new ridges curve outward ventrally, in the region of more rapid growth, and this condition becomes more and more accentuated with the addition of successive ridges, until the later ridges are bent at almost a right angle. This angle marks the division between the anterior lobe and the median lobe of the adult shell (see p. 196). The two segments of each ridge, as marked off by this angle, are morphologically one. The formation of this angle accounts for the anterior gap through which the foot is protruded.

In the meantime there has been a rapid deposition of shell at the postero-ventral margin of each valve, forming the auricle, which increases rapidly in size to provide a sufficient surface for the attachment of the rapidly growing posterior adductor muscle.

All this is accomplished, and even rudimentary pallets are developed, before the

organism has succeeded in burying its shells from sight. Thus the immediate correlation between the boring habit and the structure of the shell is illustrated.

Further growth of the shell occurs by addition of successive increments to the margin in such a way that the newly established shape of the shell is but little altered. The rate of addition of new ridges is most rapid during the first month of life in the wood, and decreases progressively thereafter, although growth probably does not entirely cease until the organism is near death. By our system of planting and removing test timbers at regular intervals in infested localities, it has been possible to get a limited number of shells whose age can be estimated with a considerable degree of accuracy. The following data were obtained by averaging the number of ridges that could be counted on 25 shells of each age. A source of error lies in the fact that, while new ridges are being added at the margin of the shell, certain of the older ones are lost by erosion or by a secondary overgrowth of shell substance, so that the figures given may represent a few less than the actual total of ridges deposited in a given time. This error seems unavoidable, and is negligible for practical purposes, since we desire principally to know what age a given number of visible ridges indicates.

Data from older shells of known age have not, in general, been available, owing to the fact that our test timbers have been, at the end of from four to six months, entirely destroyed, or so weakened that they were washed out by tidal currents or wave action. A series of 25 shells from Crockett, estimated from the length of the burrows and the period of time the pile from which they were taken was known to have been exposed, to be not less than 15 months old, averaged 38.8 ridges. A series of 20 shells from Goat Island, judged to be of approximately the same age, averaged 42.1 ridges.

TABLE No. 43

RATE OF GROWTH OF RIDGES ON SHELLS OF TEREDO AT GOAT ISLAND

Age (months)	Number of ridges	Rate of growth during month
1	9.3	9.3
2	13.1	3.8
3	16.7	3.6
4	19.3	2.6

TABLE No. 44

RATE OF GROWTH OF RIDGES ON SHELLS OF TEREDO AT CROCKETT

Age (months)	Number of ridges	Rate of growth during month
1	8.8	8.8
2	12.1	3.3
3	14.2	2.1
....	....	....
		(Mean of 4th, 5th and 6th months)
6	20.7	2.2

It will be noted that the tables show a slight but consistent advantage in number of ridges of the shells from Goat Island over those from Crockett. This is correlated with the generalization set forth above (p. 270) that the ridges are more numerous and close-set on shells of teredos from the more saline waters.

A few shells of known age were available from other localities, and these were examined as a check on the accuracy and general applicability of the above figures. From the Oakland Harbor Light Station, two miles across the channel from Goat Island, 5 shells 3 months old averaged 16 ridges; 8 shells 4 months old averaged 18.7 ridges. From Dumbarton, near the southern end of the bay, a series of 10 shells 6 months old averaged 20.5 ridges. A series of 10 shells of similar age from Angel Island averaged 20.6 ridges. The largest shell we have taken has 81 ridges. This is the shell of the specimen from the Oakland Mole, mentioned on page 233, which was 50.8 cm. long and estimated to be two years old.

The Annual Cycle

The finding of a specimen of *Teredo navalis* of an approximate age of two years is very unusual. The death rate at all stages of the life history is extremely high. Probably the great majority of the free swimming larvae become food for fishes, or otherwise perish without finding settlement on wood. Of those which find attachment, many die off during the early stages of boring, as testified by the many shallow burrows which are found empty, and the numerous surface pits which have gone no farther. In heavily attacked piling the surface punctures are always more close set than is possible for the burrows as they expand within the pile; this means that only the earlier arrivals, and those which bore most rapidly, are able to establish themselves and survive. Late comers are crowded out, and soon die for lack of space and wood in which to bore.

The organisms which are comparatively successful and succeed in becoming established in the wood and surviving for a period of months, in most cases become victims at last of their own rapaciousness. All of the available wood is devoured. Further, the substance of the piling is broken down to such an extent that it no longer affords adequate protection. Fragments are torn off by abrasion and wave action, exposing the borers, which must of necessity die in such condition. When some have died, the products of their decomposition affect others in adjoining burrows. Fungus growth and bacterial action set in, and in a short time the pile becomes a focus of death and decay, so that few of the borers are able to survive.

In consequence of these conditions, the majority of specimens of *Teredo* which enter a pile die within six months. It is safe to say that in most cases not more than 10 per cent of the specimens which find settlement on wood survive until the following breeding season. Survival for more than one year is very unusual. In the instance cited above, the organism apparently two years old was most favorably situated, boring deep in a relatively sound pile, where it was not subjected to the unfavorable effects of crowding. The pallets of this specimen were badly eroded, so that they were of little or no use in closing the orifice of the burrow, and it is probable that the animal would not have survived much longer if it had been left undisturbed by man.

Thus we may say in general that the cycle of birth, larval life, growth in the wood, reproduction, and death, is completed in a single year; and that in a majority of cases the cycle is terminated by accident or disease. Only the immense numbers of larvae produced by the relatively few survivors maintain the species at its destructive level.

CHAPTER XVIII

NOTES ON THE BIOLOGY OF OTHER PACIFIC SHIPWORMS

In view of the extended discussion of the biology of *Teredo navalis* given in preceding chapters it will suffice to mention rather briefly the salient features of the life history and habits of the several other shipworms occurring in Pacific waters, insofar as these are known. The order followed below is that of the economic importance of the organisms discussed, rather than the order of systematic zoology, which was followed in Chapter XIII, where also the characters distinguishing the various species were set forth.

Bankia setacea

This species has been called the "Northwest Shipworm" While it occurs commonly in Los Angeles Harbor and in somewhat limited numbers in San Diego Bay, its capacities for damage are most fully realized in the harbors from San Francisco Bay northward. The most northern limit of its distribution has not been determined, but its range includes the Alaskan coast, at least to Kodiak Island. The species is apparently native to the Pacific Coast of North America; it has been here since the earliest history of shipping on this coast, and has not been reported as occurring elsewhere.

In several aspects of its habits and relations to physical factors of the environment *Bankia setacea* differs so decidedly from *Teredo navalis* as to merit special remark. The breeding habits, as noted in an earlier chapter, are fundamentally different. Instead of the eggs being fertilized internally and retained in the gills of the female until a fairly advanced stage of larval development is reached, as is the case in *T. navalis*, *T. diegensis* and others, in *Bankia* the eggs are extruded into the water, fertilization and the successful development of the egg to the stage of the bivalve larva being matters of chance and considerable hazard. Hence, although an enormous number of eggs is produced by a single female, the number of larvae finding settlement is relatively small as compared with the incubatory species.

Further, the breeding season is relatively short, commencing in February or March, reaching a maximum in April or May, and as a rule coming to a close before July. Females bearing eggs apparently mature were found at Angel Island on August 24, 1921, in test boards placed April 25 preceding, and also along the San Francisco waterfront on August 18, 1922, in piling driven in February preceding. These findings would indicate the possibility of an autumn as well as a spring breeding season for this species; but the only indication of settlement of larvae later than June was the finding at Goat Island, on September 15, 1921, of one small specimen of *Bankia setacea* in a test board placed in the water July 15 preceding. It would seem therefore that the conditions prevailing during the late summer and autumn are not favorable to the development and settlement of larvae of this species.

Observations indicate that the most important single factor influencing the breeding activities of *Bankia setacea* is temperature, with which factor the breeding season appears to be inversely correlated. Thus in San Francisco Bay the breeding season begins about February, when water temperatures are nearly at a minimum for the year, and ceases in general at the beginning of summer. In Alaskan waters, where temperatures are considerably lower, the breeding season for this species begins a month or more earlier than in San Francisco Bay. A test board placed at Petersburg,

Alaska, November 1, 1922, under the direction of the National Research Council Committee, showed early stages of attack by *B. setacea* on January 2, following.

The supposition that low temperatures are favorable to this organism is supported by the fact that it occurs most commonly in deep water, and in San Francisco Bay attains maximal size in the regions of Sausalito, Tiburon, and the San Francisco waterfront. The relative scarcity of this form in localities south of San Francisco Bay indicates that it does not thrive in the warmer waters of the southern California coast.

In addition to temperature and depth, the local distribution of this species is limited by minimal salinity requirements and, to a much less extent, by sewage contamination.

Bankia setacea is much less resistant to low and fluctuating salinities than is *Teredo navalis*. This difference may be in part physiological, and in part due to the fact that the jointed, feather-like pallets of *Bankia* possibly afford a less effective mechanism than the simple pallets of *Teredo* for sealing the entrance to the burrow against the ingress of water of too low salinity. In any case, *B. setacea* is limited in its distribution in San Francisco Bay to regions where the average salinity is not much less than 25 parts per 1000, and the minimal salinity for the year probably not below 10 parts per 1000.

In this investigation *Bankia* has not been found at all in San Pablo Bay, the farthest point up-bay at which actual specimens have been obtained being Point Richmond, although it is possible that the organism occurs in deep water as far as Point San Pablo. There is one record of its occurrence for a time clear at the upper end of San Pablo Bay, at Crockett, where it was reported by Mr. A. A. Brown, as occurring in 1917-1918, in green piling that had lain awhile in the boom at Islais Creek, after which it was driven at Crockett in the period from January to June, 1917. Some burrows were detected in these piles at the time of driving, and the probable interpretation of the data is that the piles were infected with *Bankia* while in the boom in the lower bay, and that some of the organisms survived for a time in the new locality. A careful search here and elsewhere in the upper bay since 1919 has not brought to light any specimens of *Bankia*, and it does not appear probable that the organism will be able to establish itself as a serious pest in San Pablo Bay unless the salinity conditions prevailing there should become considerably and permanently altered.

The salinity requirements of *Bankia setacea* appear to be quite similar to those of *Limnoria*, and the localities occupied by these two organisms in San Francisco Bay are very nearly co-extensive, although *Limnoria*, being a hardier and more adaptable organism, will sometimes successfully invade areas where *Bankia* is unable to become established.

As regards the effect of sewage contamination, *Bankia*, like *Teredo*, does not appear to be deleteriously affected except in limited areas close to the mouths of sewers. Thus at the foot of Channel Street in San Francisco, where a large sewer opens at the head of a narrow channel, in which the sewage flows confined for several hundred yards before reaching the bay, *Bankia* occurs at least a hundred yards up the channel, where on a low tide the pH value was found to be 7.5 (.35 lower than the average for this portion of the bay), and the bottom oxygen 4.38 c.c. per liter, or .86 less than the average at the Ferry Building (see page 266). At this locality, in fact, *Bankia* seriously damaged untreated piling in a temporary structure between February and August, 1922 (see p. 237). Any ordinary degree of sewage contamination cannot therefore be regarded as an effective deterrent to *Bankia* or other borers.

The burrows of *Bankia setacea* differ from those of the two species of *Teredo* found in San Francisco Bay in two important particulars. They are larger, and they present continuous minor deviations from the main axis of the burrow, so that the burrows of *Bankia* are less symmetrical and regular than those of *Teredo* (compare figures 22 and 89). The slight ridges which occur on the walls of the burrow of *Bankia*

Fig. 116. Pile from Seattle, driven December, 1922, pulled June, 1924. Entirely destroyed at mud line by *Bankia setacea*.
(1) Split section, mud line to 1 ft. above.
(2) Section 1 ft. to 3 ft. above mud line, with bark removed.

are due to abrupt but slight changes in the direction of boring, resulting from a shift in position of the foot and shell. They are sometimes less than a millimeter apart.

The burrow of *Bankia* enters the pile at right angles to the surface as a small pinhole, and turns obliquely, usually downward, enlarging rapidly within 2 inches of the surface to $\frac{1}{4}$ inch in diameter, and within 4 inches to a diameter of $\frac{3}{8}$ to $\frac{1}{2}$ inch. The largest burrows we have found in San Francisco Bay were $\frac{7}{8}$ inch in diameter at the widest portion, and exceeded 30 inches in length.

The burrows of *Bankia* characteristically penetrate piling more deeply before turning to run parallel with the grain than do the burrows of *Teredo* in lightly infected piling. In heavily infected timbers all burrows must of necessity go towards the center; but in lightly infected piling the burrows of *Teredo* are usually more superficial than those of *Bankia*.

Bankia, even more than *Teredo*, concentrates its attack near the mud line on piling, so that its burrows, although fewer and more sparsely set than those of the latter, are capable of speedily destroying the bearing power of untreated piles, even though a few feet above the mud line the wood may be practically sound.

Teredo diegensis

This is an organism much smaller than *Bankia*, and smaller in general than *Teredo navalis*, adults ranging in length from one or two to four or five inches. The average size in San Francisco Bay is smaller than in harbors farther south.

This species is at present of negligible importance in San Francisco Bay, and its history during the four years it has been known to occur in this locality does not indicate that it is likely to become a serious economic factor here. In Los Angeles and San Diego harbors, however, quite the reverse is true. *Teredo diegensis* is in these localities most numerous and destructive, constituting the real shipworm problem of these ports.

Teredo diegensis, like *T. navalis*, is viviparous, the offspring being retained in the brood pouch of the female until a somewhat advanced stage of larval development is reached. The larvae of *diegensis* are less numerous than those of *navalis*—490 being counted in the brood sac of a female two inches long—but are considerably larger, so that the brood pouch of the female is greatly distended, the large, nearly globular, brown-shelled larvae being plainly visible through the transparent body wall of the parent (fig. 72).

The lesser number of larvae carried in the brood pouch at one time, as compared with *T. navalis*, is compensated for at least in part by the much longer breeding season. The period of breeding activity in Los Angeles and San Diego harbors, in fact, includes practically the entire year, although the settlement of larvae is much lighter during the winter months. Test boards placed in San Diego Bay in December, 1922, indicated some settlement of larvae of this species by January, although no heavy settlement occurred until May. The growth of such larvae as found settlement during the winter months was much retarded during January, February, and March, the maximum length attained by March 16 being 1/16 inch. After the first of April growth increased rapidly, a maximum length of three inches being attained by May 15.

Test boards placed in Los Angeles Harbor afforded very similar data. Boards placed in October, 1922, showed beginnings of attack by *Teredo diegensis* through November, December, January and February. A maximum length of one inch was reached by March 16. In April and May the settlement of larvae greatly increased, and the rate of growth in the wood became accelerated. By September the 2″ x 4″ blocks were entirely honeycombed by *T. diegensis*, of a maximum length of about 5 inches.

In general, then, it appears that in Los Angeles and San Diego harbors *Teredo diegensis* breeds more or less continuously throughout the year, but that settlement of larvae is heaviest and growth most rapid during the period from April to October, that is, during the warmer months of the year. Thus the temperature relations of this species are quite the reverse of those of *Bankia setacea*.

The occurrence and behavior of *Teredo diegensis* in San Francisco Bay has been

somewhat puzzling. Its distribution in the bay has thus far been limited to a small inlet about one mile north of South San Francisco. It was discovered here in 1920 by Professor Kofoid, in submerged bracing timbers under the marine ways of the Schaw-Batcher Shipbuilding Corporation (on the premises of the Western Pipe and Steel Company). A thorough search during the succeeding years has not revealed this species as occurring at any other point in the bay, and its numbers at this one locality where it has been found appear to be considerably depleted at the present time. An inspection of piling and brace timbers here on June 21, 1924, revealed only a few specimens of this organism, in company with more numerous *Teredo navalis*, and test boards placed at this time showed only a very light and scattered attack of *Teredo diegensis* when examined in September following.

There appears to be no question that the organism under discussion is true *Teredo diegensis*, and identical with that species as occurring in Los Angeles and San Diego harbors, although the San Francisco Bay specimens have been described by Bartsch (1922) as *Teredo townsendi* new species. We have compared large numbers of specimens from all three localities, and find that the differences in the pallets which Bartsch has considered to be of specific—and even sub-generic—value, are merely individual variations within the species. We have found typical *diegensis*, and the variate called *townsendi*, occurring invariably together at all localities where either has been reported, and it is usual to find these two variates, together with several intergrading forms, in the same piece of timber.

Characteristic *diegensis* has dark tipped, truncated pallets. The form which has been described as *townsendi* differs merely in having the distal portion of the blade excavated. Either form, on *drying*, may develop a distal corona such as Bartsch has described as typical of *diegensis*.

Considerable variation occurs in the color of the distal corneous portion of the pallet, which may vary from pale, transparent amber through deep brown to black. This variability is only in part an age character, although as a rule the periostracum becomes thicker and hence darker with increasing age. It often occurs, however, that in quite small specimens from the California coast the distal portion of the blade is decidedly dark. In specimens from the Hawaiian Islands, on the other hand, the corneous portion of the pallet remains quite transparent in specimens four or five months old. Whether or not the darker color later develops we do not know, as older specimens have not been available from the test blocks. On drying, the distal periostracum of the pallets of the insular *diegensis* becomes darker and more opaque, so that the pallets are hardly distinguishable from those of the California coast.

The darker corneous portion of the pallet is not infrequently partly or wholly worn away or broken off, in which case the blade of the pallet is represented simply by the oval calcareous base (fig. 72, *2* and *3*). The corneous portion can be rather readily removed from normal pallets, thus reducing them to the oval form.

We conclude that *Teredo diegensis* is particularly a pest of the warmer waters of the coast of southern California and the Hawaiian Islands. It has in some manner been introduced to San Francisco Bay, and has in a measure established itself in a small inlet near South San Francisco, where the shallow water becomes sufficiently warmed to permit the organisms to breed at least during the summer months. The history of the species in San Francisco Bay during the four years in which it has been under observation suggests that it is here able only to eke out a struggling existence under conditions to which it is not well adapted. It appears at present unlikely that this species will occasion serious damage in San Francisco Bay or harbors to the northward.

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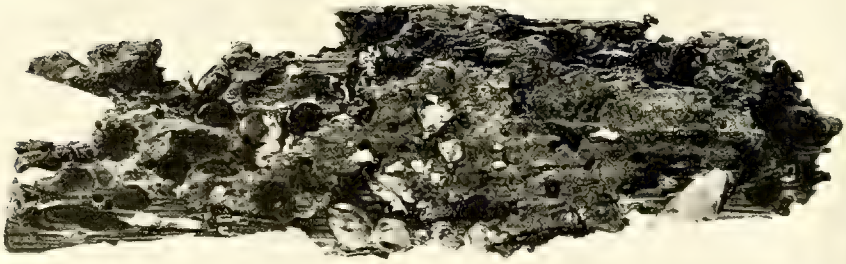

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Fig. 117. *Martesia striata.*

1. *Martesia striata* from Pearl Harbor, dorsal view. × 2.

2. Same, lateral view.

3. Same, ventral view.

4. Split section of a test block submerged five months at Cavite, Philippine Islands, showing *Martesia striata* in place in burrows. The burrows exhibiting a calcareous lining are those of *Teredo.* × 9/10.

5. Portion of the surface of a block submerged nine months at Cavite, showing destruction by *Martesia striata.* × 9/10.

Fig. 118

1. Inner surface of 1″ redwood sheathing, submerged 20 months in Pearl Harbor. *Martesia striata* coming through from outside. Looking through empty burrows, note small openings through which borers entered. At upper left is seen a strip of tarred ship's felt which they have penetrated.
(*Photo by courtesy of Public Works Dept., U. S. Naval Station, Hawaii.*)

2. Side and dorsal views of *Martesia striata*, natural size.

Martesia striata

While *Martesia striata* is not, properly speaking, a "shipworm," as a wood boring mollusk of similar habits and capacities for damage it may well be considered here. It is an organism somewhat resembling a small clam in general appearance, blunt at the anterior end and tapering somewhat posteriorly. The anterior end may be open, exposing the foot, or the gap may be closed by a smoothly rounded calcareous partition, consisting of two halves separated by a median fissure (see fig. 117, *3*). The latter condition indicates that the organism has for a time at least suspended boring activities. The species, *M. striata*, is characterized by a narrow accessory plate along both

dorsal and ventral margins of the valves, and a large emarginated dorsal shield covering the umbonal region.

This species has occurred occasionally in the test blocks sent in from Pearl Harbor, rarely more than three or four small specimens of a maximum length of 2 cm. occurring in any one block. That the organism is of economic importance in this region, however, is indicated in the photograph, figure 118, showing *Martesia* to have burrowed through 1″ redwood sheathing and a layer of tarred ship's felt within, during a period of 20 months' exposure in Pearl Harbor. Damage by *Martesia striata* and *Teredo diegensis* in a 12″ x 12″ timber exposed 10 months in Pearl Harbor is shown in figure 119. Reports from the Gulf of Mexico indicate that *Martesia* bores very effectively in creosoted timbers; but we are informed by Commander C. A. Carlson, Public Works Officer, U. S. Naval Station, Hawaii, that no evidence has been found of damage to creosoted piling in Pearl Harbor by this borer.

Burrows attributed to this organism were found in one of the test blocks sent in from Nawiliwili Bay, although the animals themselves had been lost out before the block was sent in, thus precluding certain identification.

At Cavite, Philippine Islands, attack by *Martesia* on the test blocks was rapid and extremely destructive (fig. 117), the damage occasioned by *Teredo* at this locality, although considerable, being secondary to that occasioned by *Martesia*. Blocks exposed four months or longer were usually in a crumbling condition, the surface being riddled by small *Martesia*, mostly less than 2 cm. in length.

A species of *Martesia* of uncertain identity occurred in some of the test blocks sent in from Mazatlan, Mexico. It did not appear at Topolobampo nor Guaymas nor in any harbors along the Pacific Coast farther north.

Other Species

Bankia mexicana has occurred in test blocks sent in from Mazatlan and Topolobampo, the former at the entrance to the Gulf of California, the latter a little farther north along the Gulf. The board at Mazatlan was installed August 20, 1922, and showed attack by *Bankia mexicana* in less than a month. Growth was very rapid, a length of 15 cm. being attained by the end of October. By the following April the blocks were entirely riddled and in a crumbling condition. A new board was placed here on May 1, 1923. Attack on this board commenced in June, and increased through the summer. The board at Topolobampo was placed February 1, 1923. Initial attack by *Bankia mexicana* appeared on the third block, removed March 16, but growth of the organism was much retarded until after May 1. Specimens 25 cm. long were found by the end of July, and by August 15 the blocks were thoroughly riddled.

The temperature relations of this species accordingly appear to be quite different from those of *Bankia setacea*, conditions for the growth and reproduction of *Bankia mexicana* being most favorable during the warmer months of the year.

Of the biology of *Bankia excolpa* and *Bankia orcutti* nothing is known, except that some specimens have been taken in the past in the Gulf of California. Neither of these species has come to light in our investigations.

Teredo parksi appears to be the dominant species in the Pacific Islands, being present at all localities in the Islands from which test blocks were received, except Nawiliwili, Kauai. The heaviest attack by this species occurred in Pearl Harbor. Blocks submerged here September 1 showed considerable surface attack at the end of a month, and by the end of the second month a length of 8 cm. had been attained by the largest specimens. At the end of five months the blocks were thoroughly honeycombed and beginning to crumble as a result of the combined attack of *Teredo*

and *Limnoria*. The rate of growth under normal conditions at this locality appears to be from 3 to 5 cm. a month during the first five months, at the end of which time the blocks were usually so crowded as to hinder or stop further growth. A burrow 18.5 cm. in length occurred in a block submerged five months at the United States Navy

Fig. 119. Sample of 12″ x 12″ timber submerged 10 months in Pearl Harbor. Split surface showing damage by *Teredo parksi* and *Martesia striata*, the latter organisms still in place in burrows.
(*Photo by courtesy of Public Works Dept., U. S. Naval Station, Hawaii.*)

Coaling Plant, and a burrow 22.5 cm. long was found in a block submerged at Kuahua Island, these being the maximum lengths recorded.

This species is incubatory, and in Samoan waters becomes sexually mature within a few weeks after entering the wood. Specimens containing well developed larvae in the gills were found in blocks submerged only two months at Tutuila. Potts (1923) reports that rafts in the water only twenty-four days in Pago-Pago Harbor

contained shipworms which were producing free-swimming larvae; it is probable, although not certain, that he was dealing with this species. In Pearl Harbor *Teredo parksi* appears to mature more slowly and to reach a larger size, the difference doubtless being due to temperature conditions.

In Samoa *Teredo parksi* appears to breed uninterruptedly throughout the year, but in Hawaii the breeding activity, as indicated by settlement of larvae, reaches a maximum in August, September and October, progressively decreases from November to March, and reaches a minimum, possibly ceasing altogether, in April.

Teredo bartschi, described by Clapp (1923) from Port Tampa, Florida, was found in the test blocks sent in from Nawiliwili, occurring most numerously in the blocks placed after September, and somewhat sporadically in the earlier blocks.

This species occurs rarely in San Diego Bay, not more than a half dozen specimens having come to light in two years' investigation. It seems likely that the organism has been introduced in shipping from the islands, or from Atlantic waters, and either has not found the new environment favorable, or has not had sufficient time to become established. The status of *Teredo bartschi* in San Diego Bay appears accordingly to be similar to that of *Teredo diegensis* in San Francisco Bay.

Of the biology of *Teredo affinis*, *Teredo furcillatus*, *Teredo samoaensis* and *Teredo trulliformis*, little is known except the partial distribution, as given in Chapter 2. The list of localities for these forms will unquestionably be extended with increasing knowledge of the fauna of the islands.

The test board at Nawiliwili was placed February 1, 1923. In the earlier blocks *Teredo affinis* predominates, and is very destructive; but in the blocks placed after September it is almost entirely replaced by *Teredo bartschi* and *Teredo diegensis*. A few specimens of *T. affinis* have been found in the blocks from Honolulu Harbor.

Teredo furcillatus has occurred in limited numbers in the blocks from Tutuila and Honolulu Harbor. The longest burrow recorded measured 6.7 cm. The species does not appear to be of much economic importance.

Teredo samoaensis has been found only in Samoan waters, where it occurred commonly in the blocks from a test board placed in November, 1923. This board was lost before adequate data were secured, and a second board placed the following June was not at all attacked by this species.

Teredo trulliformis occurred commonly in the blocks from Honolulu Harbor, and somewhat rarely in the blocks from Pearl Harbor and Nawiliwili. The longest burrow recorded measured 9 cm.

CHAPTER XIX

THE OCCURRENCE OF ROCK BORING MOLLUSKS IN CONCRETE

Rock boring mollusks of the family *Pholadidae* are of very widespread occurrence. Their ability to penetrate rocks of various kinds and often of considerable hardness has been a matter of both scientific and popular interest. It has been supposed that concrete in sea water might be subject to attack by such borers, but specific instances of the occurrence of these organisms in concrete marine structures are rare. A few cases of such attack have lately been reported, which it is of interest to consider in some detail.

In the work of widening the channel in Los Angeles Harbor, about November 13, 1922, it became necessary to remove some old wooden piling which had been jacketed some years previously with concrete. In looking over these piles, Mr. D. E. Hughes, M. Am. Soc. C. E., observed that some of the jackets had been attacked by borers, and he immediately investigated further. Of 18 jackets examined at this location, known as the Old Fish Cannery Wharf, across the channel from the foot of 5th Street, San Pedro, 16 were found to be more or less attacked; about 5 were considered badly attacked (6 borers or more per square foot of exposed surface); the other contained fewer, and some only an occasional, borer. The two jackets which did not contain borers stood in shallower water than the others.

The exact date at which these piles were driven could not be determined, but it was probably several years prior to 1909, at which time it became necessary to jacket them with concrete to protect them from *Limnoria* or other wood borers. The jackets had accordingly been in place 14 years. The length of time during which they were actually exposed to attack by the rock borers, however, is probably considerably less than this, as the form lumber was left in place outside the jackets and would deter the pholad borers from entering the concrete until the encasing wood was destroyed by wood borers.

One of these piles was available for examination a month later by one of the authors. The jacket was about 7 feet long, having extended from the mud line up to about mean low water. It consisted of cement mortar with no coarse aggregate (see screen test below), averaging 2½ inches in thickness, and sufficiently hard that some difficulty was experienced in breaking it up with a 15-pound iron bar to secure samples.

The outside form lumber was still partly in place. It had originally consisted of 1-inch redwood, as seen at one place where it had been protected by a cleat. Elsewhere it had been badly attacked by *Limnoria* and *Teredo diegensis*, so that only a thin shell of it remained adhering to the concrete. This thin veneer of wood, however, still covered all of the jacket except about 1 foot at the top, and one corner where the form had sprung apart, leaving a gap through which the rock borers could enter. The entire surface exposed to rock borers was not more than 5 square feet. In this area nearly 40 of the borers occurred, averaging 7 or 8 to the square foot.

The mollusks in general were a little larger than a man's thumb. The largest one found occupied a burrow measuring 1⅜ inches in diameter at its widest portion. Two borers in this jacket had penetrated the concrete until they came in contact with the wood within, but none had actually bored into the wood. One indeed had turned and continued boring in the concrete parallel to the surface of the wood, to avoid entering the latter.

Mr. Hughes reported that, of the jackets examined by him, one other was attacked more heavily than this in proportion to the surface exposed; but it consisted of a very poor mortar, badly disintegrated.

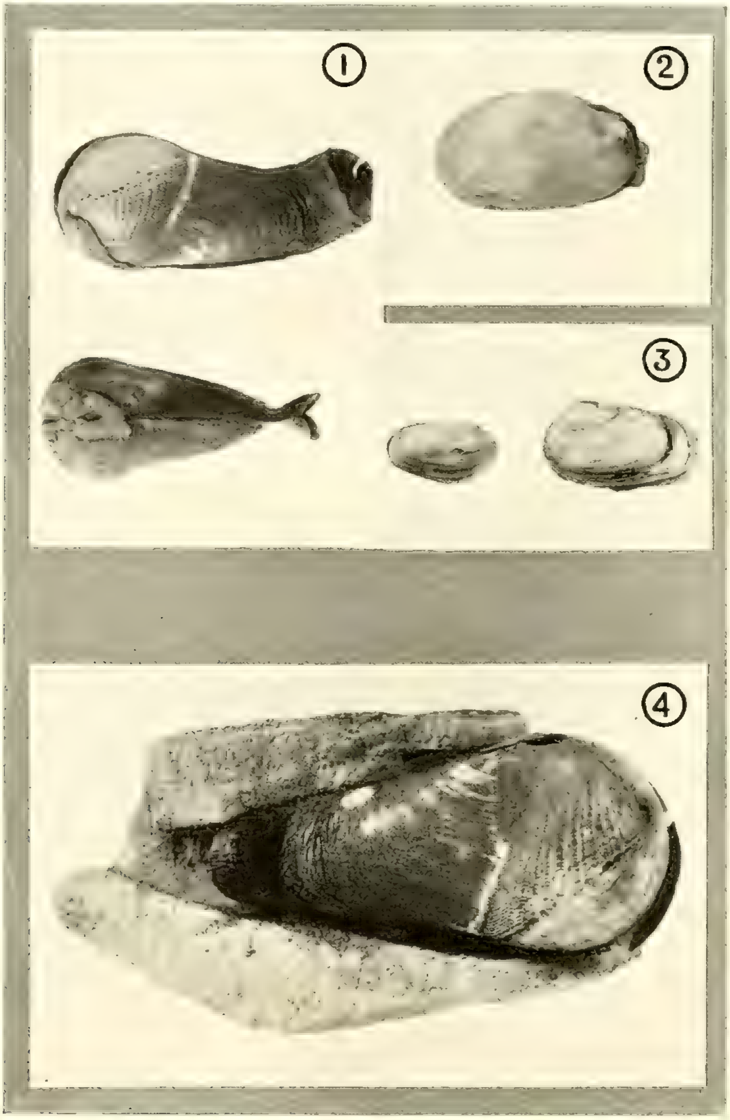


Fig. 120

1. Lateral and dorsal views of the rock clam, *Pholadidea penita* Conrad.
2. *Platyodon cancellata* Conrad.
3. *Petricola carditoides* Conrad.
4. Large specimen of *Pholadidea penita* in place in burrow.

All specimens from Los Angeles Harbor. Natural size.

The discovery of the borers at this locality led to the examination of other concrete jacketed piles in the harbor. Mr. J. W. Ludlow, Harbor Engineer, stated that of 12 pile jackets examined by him at the old Blinn Lumber Company wharf, opposite Berth 229 in Los Angeles Harbor, three were rather badly attacked by borers. Mr. W. H. Sadler, Harbor Department Chemist, reported that he had broken open 12

concrete jackets at the 1st Street ferry landing, of which three were found to be attacked, one quite badly, the others containing from 3 to 6 borers each. Of 75 such jackets examined by Mr. Sadler at the Kerckhoff-Cuzner Wharf, about 50 per cent were found to contain borers, while about 20 per cent were quite badly attacked.

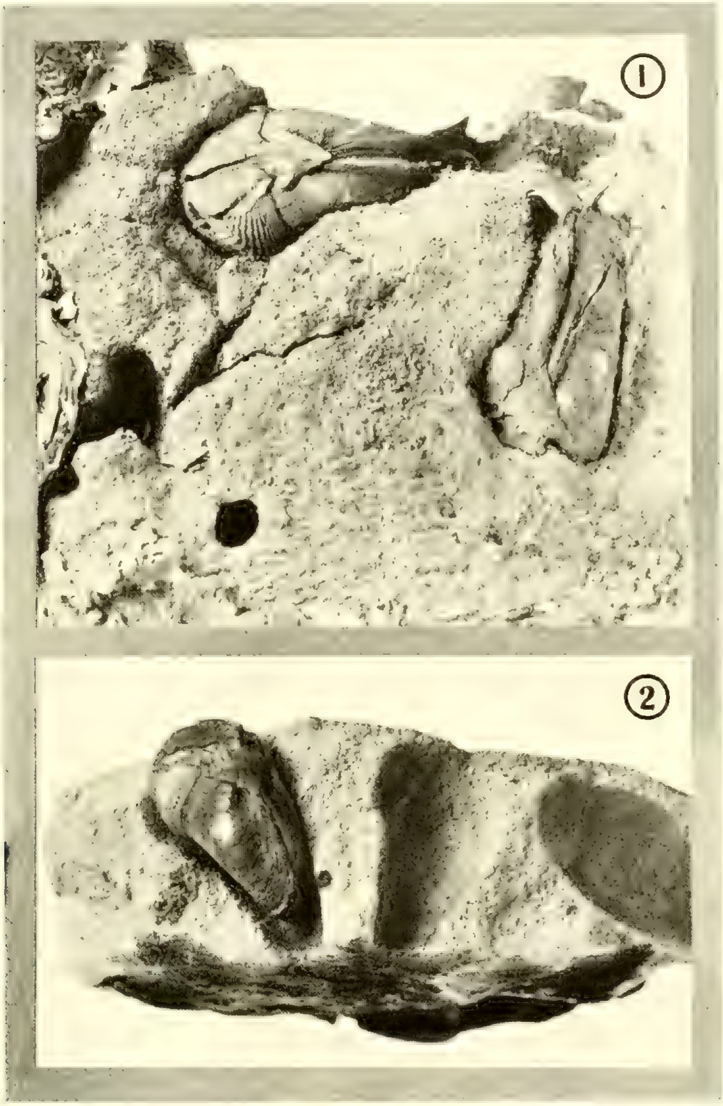


Fig. 121. (1) Sample of concrete pile-jacket containing four borers (*Pholadidea penita*) in a space 3 inches square. Two of the borers are visible, presence of the others being indicated by openings at the lower left.
(2) Section through jacket showing borer holes in close proximity. One borer (*Pholadidea penita*) in place in burrow.
Both natural size.

On December 16 Dr. Miller went over this ground with Messrs. Hughes, Ludlow and Sadler. A number of other jackets were broken open, and a considerable quantity of specimens secured. The species occasioning most of the damage proved to be *Pholadidea penita* Conrad, known commonly as the "rock clam." It was found from

2 feet above mean low water to 1 foot below, which was the lowest level at which the observers were able to work. It doubtless similarly occurs on down to the mud, even in deep water, as it has been dredged in San Francisco Bay at a depth of 50 fathoms.

This borer, unlike *Teredo*, has the body entirely enclosed within the two valves of the shell, which are ovate, tapering somewhat posteriorly, and ending in leathery flaps. During the period of active boring life the foot protrudes through a rather large anterior gap between the valves; but after cessation of boring, and perhaps in the interim between periods of boring activity, this gap is closed over by a calcareous plate, giving the borer the appearance shown in the photographs (figure 120, *1* and *4*). It will be noted that the anterior portion of the shell is ribbed and somewhat denticulated, as for rasping, or to grip the sides of the burrow.

This species is edible and is used for food in localities where it occurs in sufficient abundance to justify the labor of removing it from its rocky domicile, which is usually done by means of iron bars.

Another boring species found in these jackets was *Platyodon cancellata* Conrad (fig. 120, *2*), a near relative of the soft-shell clam (*Mya arenaria*). This borer normally inhabits stiff mud and clay. It was found in the pile jackets only sparsely, and in decidedly poor mortar.

A third species occurring in the jackets was the so-called "nestler," *Petricola carditoides* Conrad (fig. 120, *3*), which is believed not to bore on its own account, but to inhabit natural cavities or holes bored by other organisms.

As regards the extent of the damage occasioned by the rock borers, a review of the data assembled indicates that, of concrete jacketed piles at four different locations in Los Angeles Harbor, in fact, at every point in the inner harbor where such piles exist, about 50 per cent have been more or less attacked, of which rather more than one-fifth have been very considerably bored. Of those not attacked, a number stood so well inshore as to be but little exposed to the action of the borers. If all such piles were eliminated from the count, the percentage of jackets damaged would be considerably higher.

These jackets were in general of cement mortar poured around the piles by setting forms after the piles were driven. Some of the jackets had given service in sea water over a period of 14 years; but they would be regarded as decidedly inferior according to present day standards as specified elsewhere in this report. Nevertheless some of them were of considerable hardness.

Mr. A. A. M. Russell, Testing Engineer for the State Harbor Commission, made crushing tests of two of the best samples of mortar in which borers were found. One of these, a specimen 2½″ x 3½″, 4½″ high, had a crushing strength of 1726 pounds per square inch. This sample when crushed showed an encased sand pocket from which the aggregate could readily be picked with the fingers. Mr. Russell reports the grading of the aggregate as follows:

Screen	Percentages
10– 20	1.78
20– 30	.89
30– 50	4.46
50– 80	51.78
80–100	16.07
100–200	16.07
Pass 200	8.94

Approximately 93 per cent of the total aggregate passed the 50 mesh screen.

The other sample tested by Mr. Russell, a somewhat better specimen containing larger aggregate, showed a crushing strength of 3070 pounds per square inch. The dimensions of this sample were 3½″ x 3½″, 5½″ high.

The average crushing strength of a number of specimens of these jackets tested by Mr. W. H. Sadler was 2870 pounds per square inch.

Thus, while these jackets were not of high grade composition judged by present standards, a number of them were of sufficient hardness to make it a matter of some surprise that they should be attacked by molluscan borers.

We have been informed by Mr. O. Thompson of Seattle that a wharf built by him near Anchorage, Alaska, in 1901, of piling jacketed with concrete after driving, showed similar attack by rock boring mollusks. In 1914 a piece of one of the jackets was broken off accidentally about low tide level, revealing the presence of a number of rock borers about the size of a man's thumb. According to the statement of Mr. Thompson, the wooden pile thus exposed was found to contain some large shipworms and a few *Limnoria*, which had apparently gained entrance through the openings made by the rock borers in the concrete jacket.

It has commonly occurred in jacketing piles in place that the concrete has been "drowned" either by the presence of too much water in the mix or by depositing the material in water, causing segregation and laitance and rendering such structures specially susceptible to borer action. Whether or not concrete of greater hardness, containing approximately 90 per cent of assorted aggregate in excess of the 50 mesh screen, as contrasted with mortar having only 7 per cent above 50 mesh, is a matter for further investigation. An inspection of concrete jacketed piles at Pier 34 and at Fisherman's Wharf in San Francisco Bay failed to disclose any borers. The type of piling inspected here was similar in construction to the Los Angeles type in that they were jacketed in the water, but the aggregate consisted of rock and sand and produced a fairly sound concrete. It is possible that these piles have not been exposed to attack because the mud shores of San Francisco Bay do not harbor pholad borers. However, the piles at Fisherman's wharf are located within one-half mile of Fort Mason, at which location rock borers have been reported in shale rocks.

Fig. 122. *Pholadidea penita* Conrad, in place in a loose block of sandstone from Fort Mason.

CHAPTER XX

LIMNORIA AND ITS ALLIES: THE CRUSTACEAN BORERS

The foregoing chapters have dealt altogether with the wood-boring mollusks, which, in view of their remarkable adaptation to boring life and the extraordinary rapidity of their destructive work, have properly received first consideration. This should not be interpreted, however, as minimizing the importance of a second group of marine wood-boring animals, referred to collectively as the crustacean borers. This group of organisms, while less immediately and spectacularly destructive than certain of the wood-boring mollusks, nevertheless take a continuous toll of wharf piling and other marine woodwork which in the aggregate is tremendous.

The more important of them occur in waters of a salt content approaching that of the open sea; but some invade brackish waters, and even extend their activities some distance up from the mouths of fresh water streams.

The crustacean borers belong to two orders, *Isopoda* and *Amphipoda*. These may be distinguished in general by the fact that the isopods are more or less compressed dorso-ventrally, like the terrestrial wood-lice or sow-bugs found commonly in damp places, while the amphipods are laterally compressed, like the sand-fleas observed along the ocean beach.

The isopod borers constitute the more important group, including the well known genera *Limnoria* and *Sphaeroma*. The amphipod borers include two species of *Chelura*. These organisms will be discussed in the order named.

Genus Limnoria

This well known and widely distributed genus embraces six species, of which the most familiar and most important economically is *Limnoria lignorum*. This species is of almost world-wide occurrence, while the others are apparently limited in their distribution to portions of the Pacific and adjacent seas. The following account refers particularly to *L. lignorum*, with some reference to other species insofar as their distribution and habits are at present known.

Historical

Attention was called to the destructive habits of *Limnoria*, or the "gribble," by the renowned English engineer, Robert Stevenson, who found it destroying timbers used in the construction of the Bell Rock lighthouse, off the coast of Scotland, during the years 1807-1811. The animal was described as *Limnoria terebrans* by Leach, in 1814, on the basis of specimens sent to him by Stevenson. It had, however, been previously described by Rathke in 1799 and included by him in the genus *Cymothoa* as *C. lignorum*. The present and correct nomenclature was established in 1857 by White, as *Limnoria lignorum* (Rathke); he included it in the family *Asellidae*. In 1880 Harger established the separate family *Limnoriidae*, in which the genus *Limnoria* is now placed.

Moll (1915) points out that although *Limnoria* was not described until 1799, it was doubtless active long before that time. Moll states: "Dampier, the great French mariner, writes in 1723 that his ship, besides being attacked by the shipworm, also was attacked by small, white animals like sheep-lice or small locusts. Sellius (1733) figures these animals and calls them '*Springertje*.' The '*Deichgrafen von Drechterland*'

relate in their famous report of the year 1731 on the destruction of the dykes of Holland by the ship-worm that Springertje were also to be found in millions."

An examination of the figures 9 and 10 of the monograph by Sellius (1733) and of the text in paragraph 116, Chapter III, does not indicate that he was observing *Limnoria*. The organisms he figures have but five pairs of legs, are of a greenish color with red spots, have very large antennae and a tapering posterior end, and do not appear to be flattened dorso-ventrally, but are more nearly round. The general appearance is that of *Corophium* or some related amphipod. It is difficult to account for the color, which Sellius calls "subviridis." The organisms were taken from piles. The frequent occurrence of *Corophium* with *Limnoria* on piles leads one to believe that the destruction was being caused by *Limnoria*, but that Sellius was not careful

Fig. 123. *Limnoria* in place attacking wood. × 5.

to distinguish the two animals. It does not appear that he was figuring the same animals mentioned by Dampier as attacking his ship.

Limnoria lignorum has been reported as occurring along practically the entire coast of Europe. Sars (1897) records it in his "Crustacea of Norway." In 1869 it was reported from the Shetland Islands by Norman. Calman (1919) states that it occurs from the Lofoden Islands, off the coast of Norway, north of the Arctic Circle, to the Black Sea. Moll (1915) calls attention to its presence in the Black Sea and the Baltic. Calman (1919 and 1921) records it in the Southern Hemisphere from the Falkland Islands, South Africa, Australia, and New Zealand.

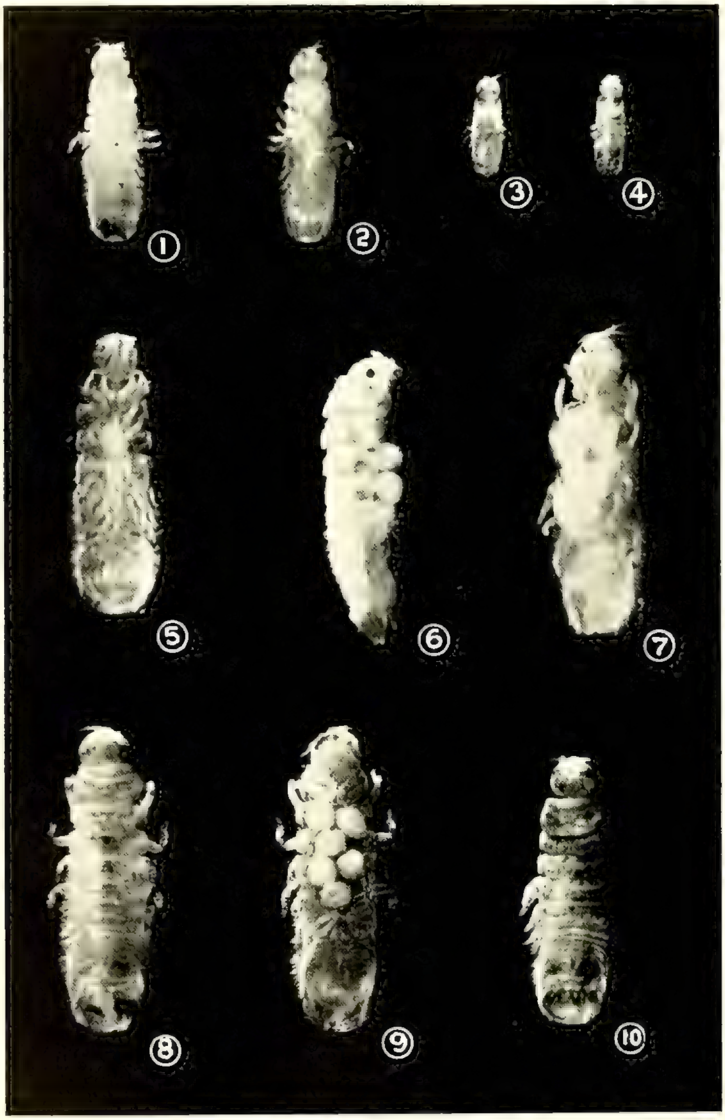


Fig. 124. *Limnoria lignorum* (Rathke). 1-4, young stages; 6, 7 and 9 females with eggs. × 11.

In American waters, Leidy found *Limnoria* on the New Jersey coast in 1855. In 1873 it was reported by Verrill as occurring from Long Island Sound to Nova Scotia.

Harger states in 1880 that the organism was distributed generally along the Atlantic coast from the Gulf of St. Lawrence to Florida. In 1874 Hewston found a species of *Limnoria* in San Francisco Bay, which he provisionally called *L. californica*, but which was undoubtedly *L. lignorum*.

Other species of Limnoria have since been described. *L. segnis* was discovered in New Zealand in 1883 by Chilton; *L. antarctica* was described by Pfeffer (1887) in Part 1 of the "Crustacea of South Georgia." Stebbing in 1906 described *L. pfefferi* from the atoll of Minikoi in the Pacific. Stebbing gives a summary of the characteristics of the above species in his account of the Isopoda from the Maldive and Laccadive Archipelagoes. *L. japonica* was described by Richardson in 1909, from the waters south of Japan. The most recent species is *L. andrewsi*, described by Calman from Christmas Island in 1910, and lately reported by Miller (1924c) from Hawaii and Samoa. All of the above are wood borers excepting the species *pfefferi* and *antarctica*, which were found on kelp.

It has been suggested that shipping may have been a factor in bringing about the cosmopolitan distribution of *L. lignorum*, the method of transfer being ballast water in the case of steel-hull ships, and infected bottoms in the case of wooden ones. Although neither method has been established definitely as operative, it is conceivable that, in the intake of some tons of ballast water by a ship lying at a wharf, the piles of which are infected, many small organisms of all kinds, including *Limnoria* and other crustaceans, will be taken in. Rubbing and chafing of the ship against the wharf may remove small fragments of wood which carry *Limnoria*, and these may then be drawn in with the ballast water. Certainly the prevalence of this organism in maritime countries generally indicates that shipping has, by one means or another, been a considerable factor in its distribution.

The Morphology of Limnoria

The external morphology of *Limnoria* has been well described by several authors. Excellent figures of the external form and of the internal anatomy are to be found in the paper by Hoek (1893).

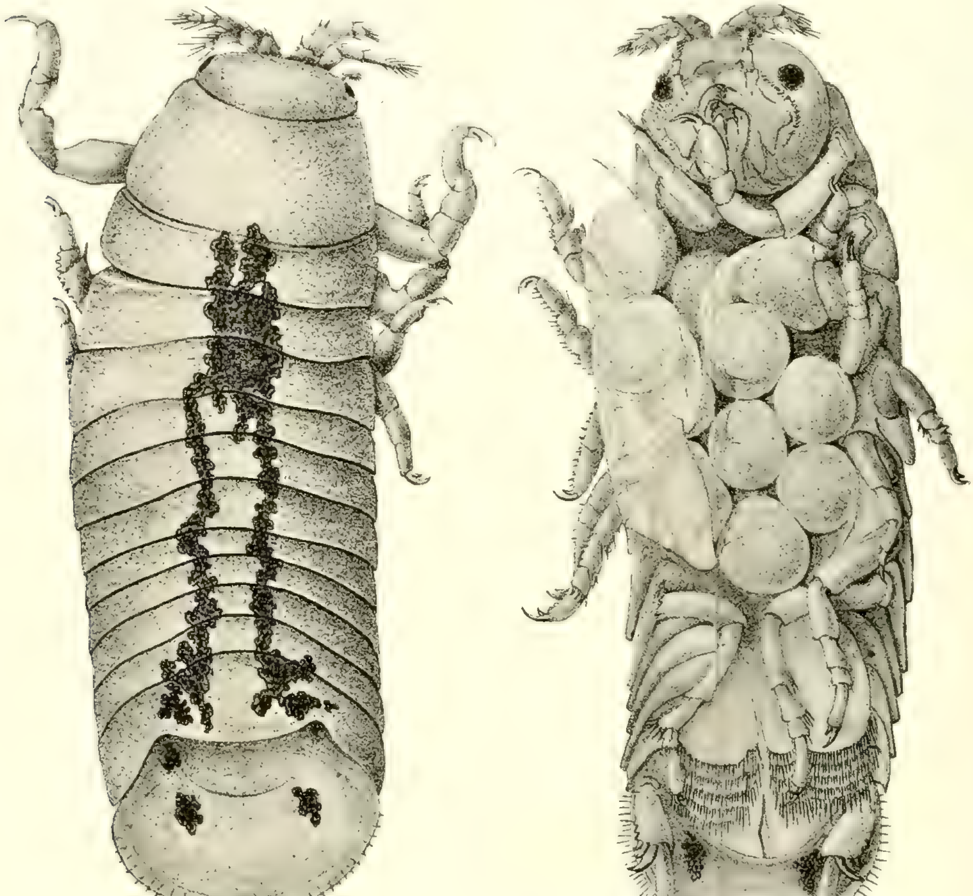
The animal is a rather generalized isopod. The body is sub-cylindrical and elongated (fig. 125). The eyes are small and are sessile. Both pairs of antennae are short. As is the rule in this group, the first thoracic somite is indistinguishably fused with the head, and the corresponding pair of appendages are modified to serve as mouth parts (maxillipeds, see below). The remaining seven thoracic segments are free as are the first five abdominal ones. The sixth abdominal somite is fused with the telson, and the last pair of appendages, the uropods, seem, therefore, to arise from the latter.

Each free thoracic somite bears a pair of walking legs. The first five abdominal somites each bear a pair of thin, plate-like appendages, pleopods, that serve both for swimming and for respiration. The last abdominal somite bears the uropods as mentioned above.

As there is no doubt that *Limnoria* accomplishes its boring by means of the *mouth parts*, it is of interest to mention briefly their chief characteristics.

The mouth parts consist of the following paired structures, from anterior to posterior: the *mandibles*, the *first maxillae*, the *second maxillae*, and the *maxillipeds*. These mouth parts, being movable, are to be distinguished from the upper and lower lips and the *metepistomum*, a hard reinforcing chitinous plate above the upper lip. The general arrangement of the mouth parts is shown in figure 126. The mandibles, maxillipeds, and first and second maxillae are shown in figures 127 and 128.

The mandibles are the most heavily constructed of any of the mouth parts. The basal part is wide and quite straight while the distal part is curved inward, giving the sickle-shaped appearance shown in the figures. The inner edge bears a small enlargement which Harger (1880) has suggested is comparable to the molar process of other Crustacea. The two mandibles are not exactly alike (see figure 127). The tip



1 2

Fig. 125. *Limnoria lignorum*. 1, Dorsal view of male. 2, Ventral view of gravid female. × 28. After Hoek, 1893.

of the left bears the most conspicuous teeth. The dentition varies with the individual. The teeth may be large and set in definite rows on the tip, or they may be smaller and not so definite. There may be a set of rounded teeth in the region opposite the molar process, but these are entirely lacking in many individuals. The mandibular palps have three joints and a varying number of bristles. Above the point where the palp joins the mandible proper is a large rounded tubercle. The first and second maxillae and the maxillipeds, in contrast to the mandibles, are leaf-like in structure, suggesting their use as organs for sweeping the particles of wood into the mouth. The first and second maxillae have simple straight bases and branched tips. The

first maxilla is biramous; the endopodite is the smaller of the two parts. The maxilliped is larger than the maxilla, and is jointed and fringed with hairs. The epipodite is triangular in shape and bears very fine hairs. The inner lobe of the endopodite has a very small palpus ending in a claw. When in place the maxillipeds overlie the maxillae at the tips, but not at the bases.

To summarize, we find that the mandibles are large, denticulated organs designed for cutting into the wood and crushing it. The remaining mouth parts are so constructed as to be of service in carrying the wood particles into the mouth, after their preparation by the mandibles.

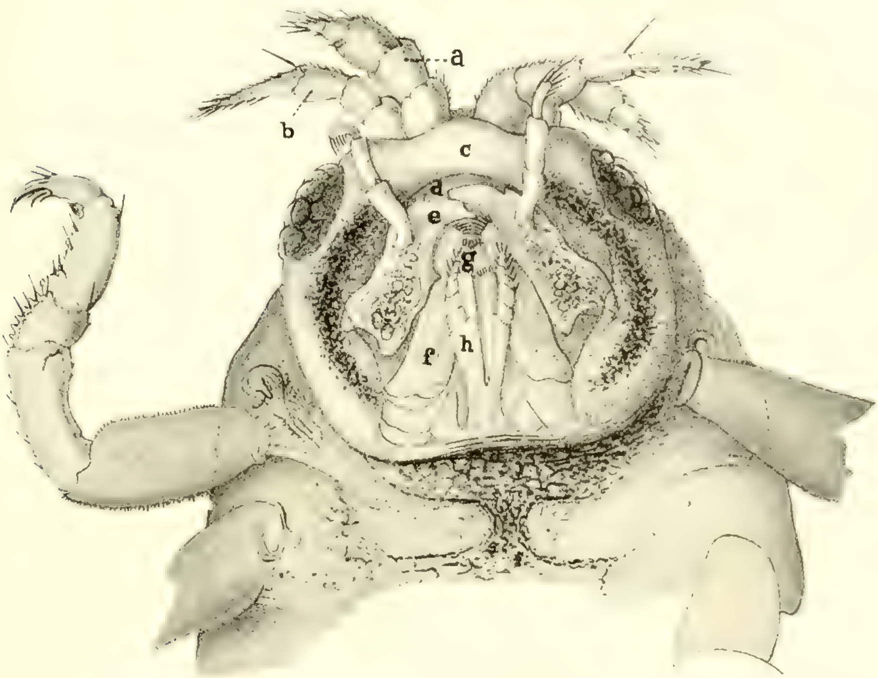


Fig. 126. *Limnoria lignorum*, ventral view of head of male:

a. First antenna.
b. Second antenna.
c. Metepistomum.
d. Labrum.
e. Mandible.
f. First maxilla.
g. Second maxilla.
h. Maxilliped.

× 56. After Hoek, 1893.

The several species of *Limnoria* do not differ greatly in external form. The characters used in determining them are as follows: the relative length of the epipodite of the maxilliped and its basal joint; shape of the outer ramus of the uropod and its size in relation to the inner ramus; the maxillary palps, diarticulate or triarticulate; the shape of the telson and the number of tubercles and ridges upon it; the size and contour of the body and its color; and habitat of the organism—wood or kelp. In *L. lignorum* the epipodite of the maxillipeds is shorter than the basal joint. The outer ramus of the uropod is shorter than the inner, and is claw-like in appearance. There seems to be some variation in regard to the number of tubercles and ridges on the telson. Bate and Westwood (1868) figure a median dorsal carina on the telson, while Sars (1897) does not. Some variation in these characters has been observed in the San Francisco Bay specimens. The characters of the organism occurring in San Francisco

Fig. 127. Mandibles of *Limnoria*. Above, outer or ventral aspect; below, inner or dorsal aspect. × 136. After Hoek, 1893.

Fig. 128. Mouthparts of *Limnoria*. 1, First maxilla. 2, Second maxilla. 3, Maxillipeds. × 136. After Hoek, 1893.

Bay correspond closely to those of *L. lignorum* and it should undoubtedly be included in that species.

The INTERNAL MORPHOLOGY of *Limnoria* is typical of the isopods. We have indicated the general arrangement of the organs in figure 129. This drawing is a reconstruction from a series of longitudinal celloidin sections, of a thickness of 50 microns. The plane of section of the figure is approximately median.

The nervous system is modeled on the arthropod plan. The brain (*br.*, figure 129) occupies the anterior part of the head and is rather closely surrounded by the muscles of the mouth parts. It consists of two main lobes, one on each side of the median line. Dorsal to each main lobe is a smaller median lobe. Laterally and ventrally are two large optic lobes which connect by a short nerve directly with the eye. The commissure which passes around the oesophagus is quite wide and connects with the wide ventral nerve cord. There are four large main ganglia on the ventral nerve cord of the head region ($gang.^{1-4}$, fig. 129). Their peripheral connections cannot be stated with certainty, although the first is probably the mandibular, while the last goes to the maxillipeds and is, therefore, the first thoracic ganglion. The nerve cord passes from the head to the thoracic region by a narrow connection. There are seven large ganglia here (*1-7*, fig. 129), the first and third being the largest. The abdominal ganglia (*I-V*, fig. 129) are five in number and more or less fused with one another.

The *circulatory organs* consist of the *heart*, *pericardium*, and *connecting blood sinuses*. The heart (*ht.*, fig. 129) lies in the median dorsal line within the pericardium (*pc.*). It extends from the anterior part of the fifth abdominal segment to the anterior part of the fourth thoracic. In cross section it shows two small ventrally lying pear shaped bodies of reticular tissue, which Hoek (1893) considers to function as valves. In the longitudinal section figured, the entire median ventral extension of the heart is not indicated, but it can be seen in the cross section (fig. 130, *2*) to extend to the digestive tract (*int.*). The arterial system, which is usually well developed in isopods, has not been worked out. The pericardium is a large cavity partially surrounding the ovaries and containing considerable reticular connective tissue. The irregular spaces within the connective tissue are filled with blood on its way to the heart. The lateral walls of the heart show thin strands running irregularly obliquely, which are the contractile fibers of the heart.

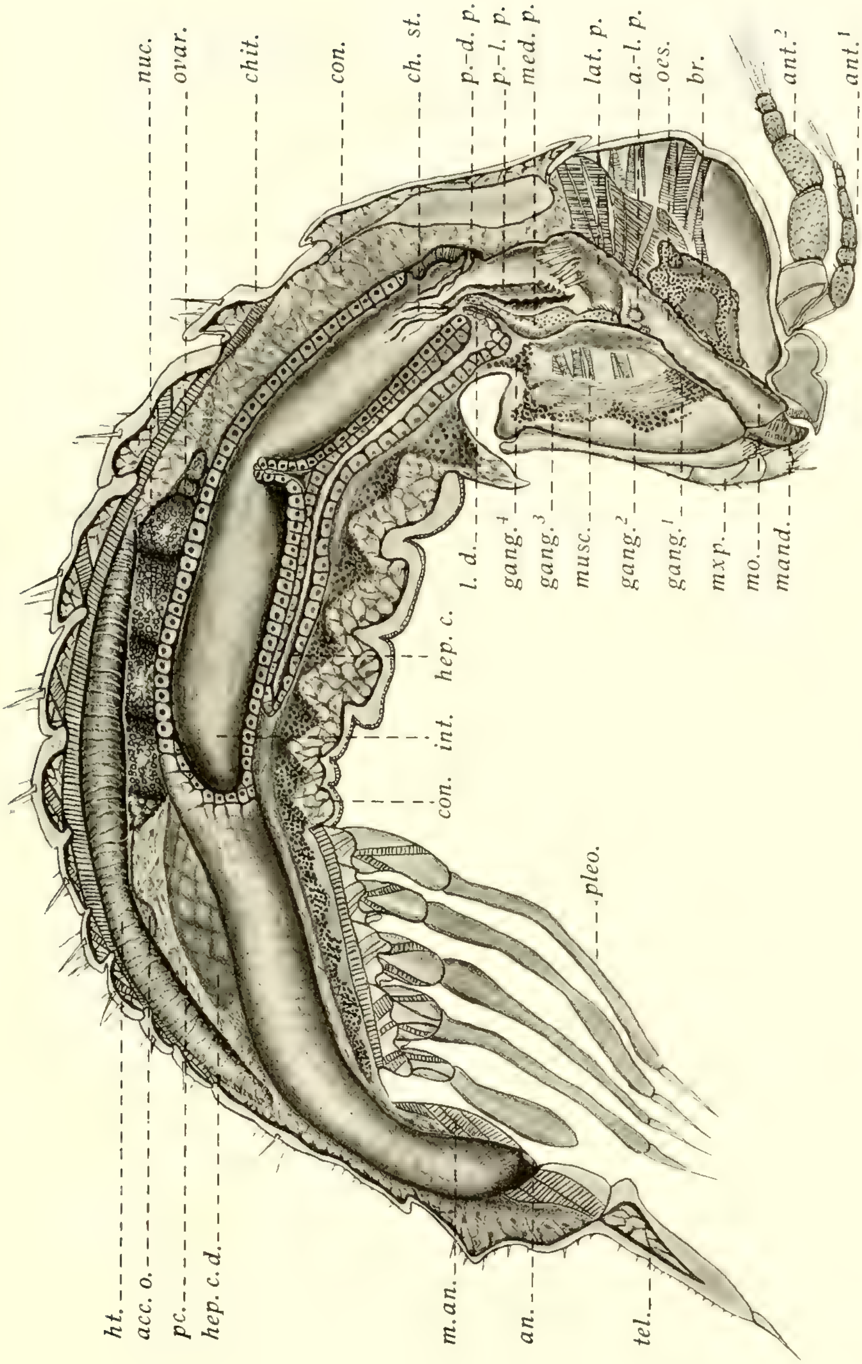
EXPLANATION OF FIG. 129

Internal anatomy of *Limnoria lignorum*, reconstructed from sections. Median longitudinal view. Magnification about 60 diameters.

a.-l. p.	Antero-lateral process of gastric mill.
acc. o.	Accessory organ of ovary.
an.	Anus.
$ant.^1$	First antenna.
$ant.^2$	Second antenna.
br.	Brain or supraoesophageal ganglion.
ch. st.	Chitinous strands attached to the postero-lateral and postero-dorsal pieces of gastric mill.
chit.	Chitinous cuticula.
con.	Connective tissue.
$gang.^{1-4}$	Ganglia of the ventral nerve cord in the head region.
hep. c.	Right ventral hepatic caecum.
hep. c. d.	Left dorsal hepatic caecum.
ht.	Heart.
int.	Intestine.
l.d.	Liver duct.
lat. p.	Lateral process of gastric mill.
m. an.	Muscles of anus.
mand.	Mandible.
med. p.	Median process of gastric mill.
mo.	Mouth.
musc.	Muscles to floor of masticatory stomach.
mxp.	Maxilliped.
nuc.	Nucleus of ovarian egg. Yolk granules are shown around it.
oes.	Oesophagus.
ovar.	Ovary.
p.-d. p.	Postero-dorsal process of gastric mill.
p.-l. p.	Postero-lateral process of gastric mill.
pc.	Pericardium.
pleo.	First pleopod.
tel.	Telson.

1, 2, 3, 4, 5, 6, 7. Ganglia of ventral nerve cord in thoracic region.

I, II, III, IV, V. Ganglia of ventral nerve cord in abdominal region.


nuc.
ovar.
chit.
con.
ch. st.
p.-d. p.
p.-l. p.
med. p.
lat. p.
a.-l. p.
oes.
br.
ant.^{2}
ant.^{1}
ht.
acc. o.
pc.
hep. c. d.
m. an.
an.
tel.
pleo.
con.
int.
hep. c.
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mxp.
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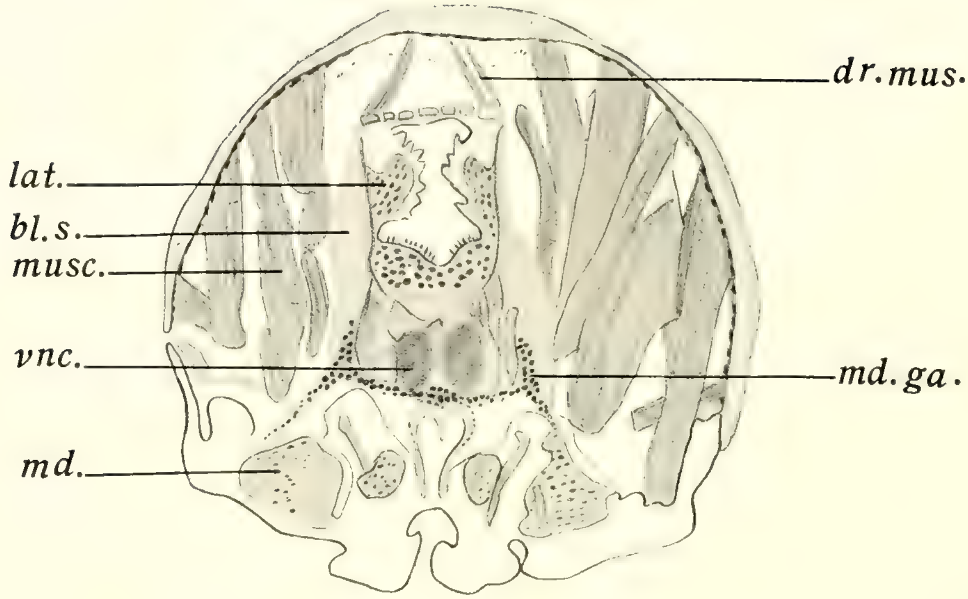
Fig. 129



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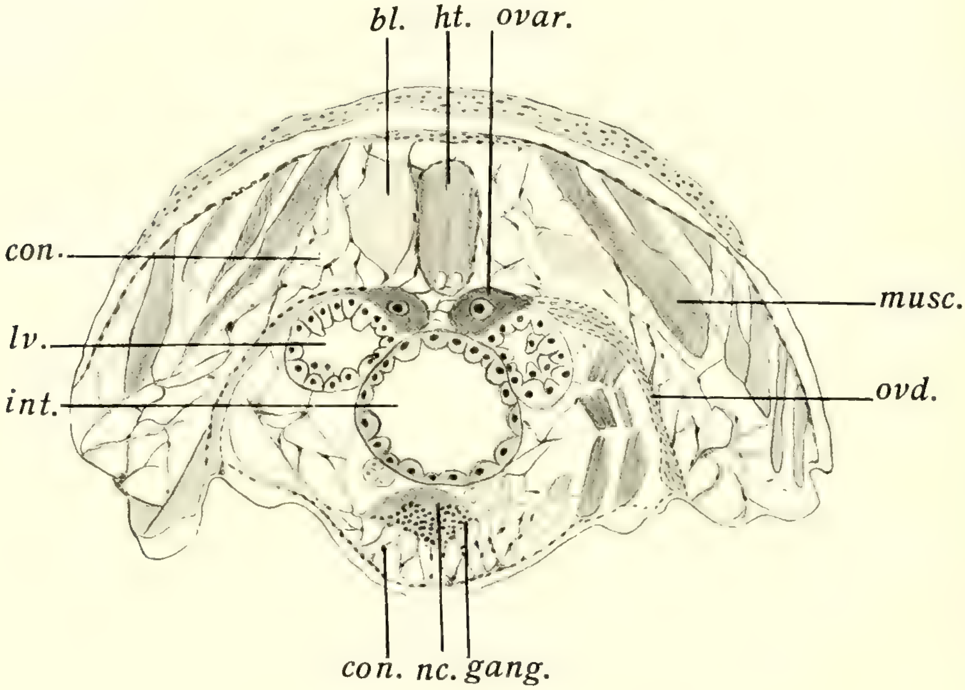

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Fig. 130. Cross-sections of *Limnoria lignorum.*

1. Head region. × 80; *bl. s.*, blood sinuses lateral to stomach; *dr. mus.*, dorsal muscle to the gastric mill; *lat.*, lateral process of gastric mill; *md.*, base of mandible; *md. ga.*, mandibular ganglion; *musc.*, muscles of mandible; *vnc.*, ventral nerve cord.

2. Thoracic region. × 80; *bl.*, blood veins lateral to heart; *con.*, connective tissue ventral to the ventral nerve cord, and in the pericardium; *gang.*, ganglion of ventral nerve cord; *ht.* heart; *int.* intestine; *lv.*, liver lobe; *ovar.*, ovary containing eggs; *ovd.*, oviduct; *musc.*, muscles of the legs.

The *digestive tract* of *Limnoria* consists of the *oesophagus*, the *masticatory stomach* containing the *gastric mill*, the *intestine* and the *anus*. The mouth (*mo.*, fig. 129) opens into the oesophagus between the mandibles and the overhanging upper lip or labrum. The latter fits closely against the mandibles. It bears a set of very fine parallel teeth. The oesophagus (*oes.*) is a nearly straight tube lined with chitin. It enlarges under the brain to form the stomach.

This masticatory stomach is lined with chitin and its walls are much folded, forming the characteristic plate-like processes found generally in the Malacostraca. There are nine of these processes in the gastric mill of *Limnoria*. We will designate them as the paired *antero-lateral*, *lateral*, and *postero-lateral*, and the unpaired *antero-ventral*, *median* and *postero-dorsal*. Of these, the lateral process, the middle process and postero-lateral processes are the largest. The others are less conspicuous, and apparently were overlooked by Hoek (1893) in his description of the gastric mill.

The lateral processes (*lat.*, figs. 129 and 130, *1*) are situated just posterior and dorsal to the smaller paired anterior-lateral processes (*a.-l.p.*). They carry large bristles with forked ends which point inwardly and posteriorly. There is a heavy muscle bundle which is inserted on the side and originates in the roof of the head. The floor of the gastric mill and stomach is considerably thickened and several muscle bundles are inserted at this level (*musc.*). As Hoek did not observe the most anterior of the lateral processes, those structures which he calls the "antero-lateral processes" are here designated as the *lateral processes*.

The postero-lateral processes (*p.-l.p.*, fig. 129) are paired and arise from the ventral wall of the gastric mill, on both sides of the mid-line. Their dorsal surfaces are flat and the sides concave. At the posterior end of these processes, close against the wall of the gastric mill, they bear two small prolongations. Narrow strands of chitin are attached to these prolongations and trail posteriorly into the intestine. The postero-dorsal process (*p.-d. p.*) also ends in chitinous strands at the same level. The median process (*med. p.*) arises at nearly the same level as the lateral process, and anterior to the postero-lateral processes. It consists of a ridge in the mid-ventral line, and lies between the postero-lateral processes. These processes overhang it in the mid-line. Its anterior part bears very fine hairs, but that portion lying between the postero-lateral processes does not appear to have these hairs on its surface. The middle piece is much reduced at the posterior end of the gastric mill. At this level two ducts from the livers empty into the cavity lateral to the middle process and between the overhanging portions of the postero-lateral processes.

On account of the liberal supply of muscles to the gastric mill there is little doubt that these processes can be brought into play as grinding mechanisms. This is in accord with the general view that the gastric mill is primarily an organ for the trituration of ingested material. The large bristles on the lateral processes, the sharp chitinous edges of the postero-lateral processes, and the pointed, spine-like protrusions on the antero-lateral and antero-ventral processes lend further support to this view.

Just behind the masticatory stomach, the two liver ducts (*l. d.*, fig. 129) open into the digestive tube. These openings are always into the endodermal *mid-gut*, but the posterior limits of this morphological region have not been determined in *Limnoria*, so the rest of the digestive tract is referred to as the intestine (*int.*, fig. 129). The anus (*an.*, fig. 129) is on the ventral side of the telson.

The so-called liver consists of four elongated secretory caeca, a larger pair dorsolateral to the digestive tract and a smaller pair ventral to it (*hep. c.d.*, *hep. c.*, fig. 129; *lv.*, fig. 130, *2*). The two caeca on each side open by a common duct.

The livers secrete a yellow crystalline substance. These crystals are character-

istically diamond shaped, and their yellow color is very marked. They can be seen in both the living organism and in celloidin sections. Their color and shape are suggestive of crystals of uric acid.

These crystals do not appear to be identical with the inorganic granular mass occurring in the reticular connective tissue of the pericardium. This mass is of a highly refractile substance and can be seen through the dorsal body wall. It occurs in both male and female animals (fig. 131), even in the very young organisms and those still within the brood-pouch. This granular mass is well shown in the photograph of the young organisms in figure 124 and in the drawing (fig. 125). In outline it is roughly the shape of the letter H. It has been observed in animals which have been starved for a period of a month, so that it is not to be considered as reserve food stuff. Its function is not known.

Fig. 131. *Limnoria lignorum*, photographed alive in position in burrows. $\times$ 4.

The *reproductive organs* in the female consist of two large ovaries (*ovar.*, fig. 129) and the paired oviducts. There is also a small sac-like organ (*acc. o.*, fig. 129) connected with the posterior end of the ovary. It contains some loosely arranged cells with irregular or pointed margins. Since it does not appear to be a seminal receptacle, it is possible that these cells are nurse cells and that the connecting strand with the posterior end of the ovary forms a *nutritive channel*. The eggs with the greatest accu-

mulation of yolk are found in the middle part of the ovary. In this region the nucleus shows long, fine radiations in contrast to the round nucleus of the early egg. The longitudinal section figured shows two small eggs and the larger eggs in the middle part of the ovary. The pair of oviducts is shown in the cross section (*ovd.*, fig. 130, *2*). They open on the ventral side of the fifth free thoracic segment.

The reproductive organs in the male were not studied closely. According to Hoek (1893), they consist of the *testes*, the *vasa deferentia* and the *penis*. The testes are in the last thoracic segment and in the same relative position as the ovaries of the female. They continue into the vasa deferentia, which open on the ventral side of the last thoracic segment, in the median plane of the body. The penis is implanted in a posteriorly directed fold of the skin. Hoek suggests that this fold takes the place of the copulatory scale which is found in *Idothea*.

During the growth of the ovarian eggs, some very striking changes occur. The eggs grow to a large size and the accumulation of yolk in the egg is so great as to occupy about two-thirds of the interior of the organism. The other organs are pushed

Fig. 132. *Limnoria lignorum*, photographed alive in position in burrows. × 12.

to one side. The digestive tract is tightly compressed and the livers pushed closely against it. It was noticed that no wood could be found in the digestive tract at this time.

The Boring Habit of Limnoria

The boring habit will be considered together with the methods of distribution of *Limnoria* and the initiation of attack. The possibility of distribution over long distances, from harbor to harbor, has been considered above in connection with the cosmopolitan nature of the organisms. It should be mentioned that the practice of taking in ballast water is quite common with harbor freight boats and may also be a factor in the local distribution of this pest.

By whatever means its distribution may be accomplished, the infection of untreated wood exposed in places where *Limnoria* is known to occur is very regular and rapid. Test timbers exposed at several localities in the lower bay have uniformly been attacked within one month, which is the minimum length of exposure of our test pieces. This has been the case during every month of the year. These test boards when exposed further from two to twelve months showed regularly increasing severity of attack following the initial infection.

Excluding the somewhat problematical distribution by shipping, it was assumed that *Limnoria* may be distributed either as separate free-swimming individuals, or collectively, attached to driftwood and inhabiting burrows in its surface.

Among the factors which would be important in distribution of separate individuals, special attention was given to their swimming activities, their reaction towards wood and wood extractives, and their ability to exist without a supply of wood for a considerable time, assuming it to be the main source of their food.

If *Limnoria* acts as its own agent of dispersal one would expect to find some method of locating and recognizing wood under water rather than dependence on chance contact therewith. In the case of teredo larvae, Harington (1921) has obtained evidence that there is a wood extractive to which these organisms are positively chemotropic. He obtained this extractive not only with ether and alcohol, but also with sea water; indicating therefore that such an extractive may be an effective agent in inducing the settlement of these larvae on wood. The case of *Limnoria* is, however, somewhat different from that of *Teredo*. It is necessary for teredo larvae to locate wood on which they may settle within the limited period of their larval life. The condition in *Limnoria* is nearly the reverse. The very young, recently hatched, organism does not swim at all, but gradually acquires this ability as it grows. At any time in the entire adult life, it may be transported to new locations and, so far as we know, there is no critical or limited period in which the organism must find its new location in order to survive. So, while a chemotropic mechanism for locating wood would be an aid in the dispersal of *Limnoria*, it would not appear to be absolutely essential.

Animals living under observation in aquaria have not shown any definite chemotropic reaction toward wood. Specimens introduced into an aquarium containing blocks of wood swim about in a random fashion and do not exhibit any behavior which it would be possible to interpret as a tropism or sensitivity to the presence of the nearby wood. They may come within a fraction of an inch of the wood and continue in their course without settling upon it. It has been observed, however, that water-soaked wood is more likely to be attacked than is wood recently introduced to the aquarium. It is difficult to tell whether this fact has a chemical or a physical basis. A similar reluctance to attack fresh wood has been observed in the case of teredo larvae.

In an experiment to determine how long *Limnoria* can exist without wood, some organisms were kept alive in a dish of sea water for over six weeks. At the end of thirty days some of these animals were introduced into another aquarium containing some pieces of well soaked wood. It was surprising to find that they exhibited no special avidity for the wood and no swimming reactions which showed a sensitivity to its presence. Some were then drawn into a pipette and placed on the wood. After exploring its surface they swam away from it. This test was repeated several times with the same result. The animals did not attack the test piece any sooner than those organisms which had recently been removed from their burrows. It would seem that if *Limnoria* utilized a chemical sense to detect wood it would be particularly

reactive after what may be called "wood starvation." This does not appear to be the case from the above experiments.

In order to test the point further, an extract of fine Douglas fir sawdust was made, using sea water as the extracting agent. The mixture was boiled in an ordinary reflux condenser so that the filtered extract was isotonic with sea water. It was not concentrated by evaporation. In order to form a localized center for the diffusion of the extract, a small wad of lens paper was soaked in it and placed in an oblong pan containing fifty *Limnoria*. At the other end of the pan another piece of lens paper was placed as a control. Although these organisms were quite active and swam the length of the pan repeatedly, they did not exhibit any preference or tropistic reaction toward the lens paper which had been soaked in the wood extract. After three days, the majority were not attracted to either piece of lens paper. There were a few more organisms on the control paper than on the piece which had been soaked in the extract.

It was thought that the temperature of the extraction might have altered some of the constituents to which *Limnoria* is sensitive. Some sawdust was accordingly placed in the lower half of a thin walled test tube which had been drawn out so that its aperture was reduced about one-half. It was then placed in a pan with a large number of *Limnoria*.

The distribution after two days appeared to have no relation to the wood in the test tube. The organisms were generally dispersed throughout the pan. This type of experiment, with minor variations, has been repeated on several occasions, with invariably negative results, which leads us to believe that in the case of *Limnoria* there is no chemotropic response to wood extractives which is an effective agent in the dispersal of the organisms and the initiation of their attack on wood.

In order to determine how long *Limnoria* can exist without wood the following experiment was carried out. Two three-liter jars of sea water were arranged so as to be cooled from the outside by water pumped up from the bay. Thirty-eight organisms were put in each jar. There was no wood of any kind in either jar. In both jars the organisms lived for over six weeks and were able to swim about when disturbed. At the end of this time a few of the individuals in one jar were dead; in the other jar all appeared to be normal. This ability to live without wood for a considerable period is a factor in favor of survival of the isolated organisms.

While *Limnoria* is able to swim for short distances, it does not appear that swimming can account directly for its distribution. The greatest linear distance we have observed an animal to swim is about three feet. The swimming tends in a general upward direction and as soon as it ceases the organism rapidly sinks. The tendency to sink rapidly necessitates a vigorous action of the pleopods, by means of which the swimming is accomplished. The organism swims on its back, in a series of short darts which result in a spiral or irregularly curved path. Such a course would appear to increase the probability of the organism's coming in contact with a pile or other structure while being swept about by tidal currents. But, as pointed out above, *Limnoria* does not remain suspended in the water and is only able to keep itself from sinking rapidly by a vigorous action of the pleopods; this fact makes the distribution of unattached *Limnoria* by tidal currents of doubtful importance.

In order to determine whether or not *Limnoria* exhibits any reaction to light, a well soaked piece of pine wood was placed in an aquarium in a vertical position and maintained there by a cross-piece. The vertical position is essential since wood in a horizontal position accumulates considerable sediment on its upper surface, hence the lower and darker surface would be more likely to be attacked. The aquarium was illuminated from one side, the other sides being blackened, and the test-piece was so

arranged that one-half was in its own shadow. The attack of *Limnoria* on both sides of the piece was very nearly equal.

The fact that *Limnoria* attacks a pile at all levels from mid-tide down to a depth of 40 feet or more, where it is considerably darker, indicates that there is no effective reaction to differences in illumination.

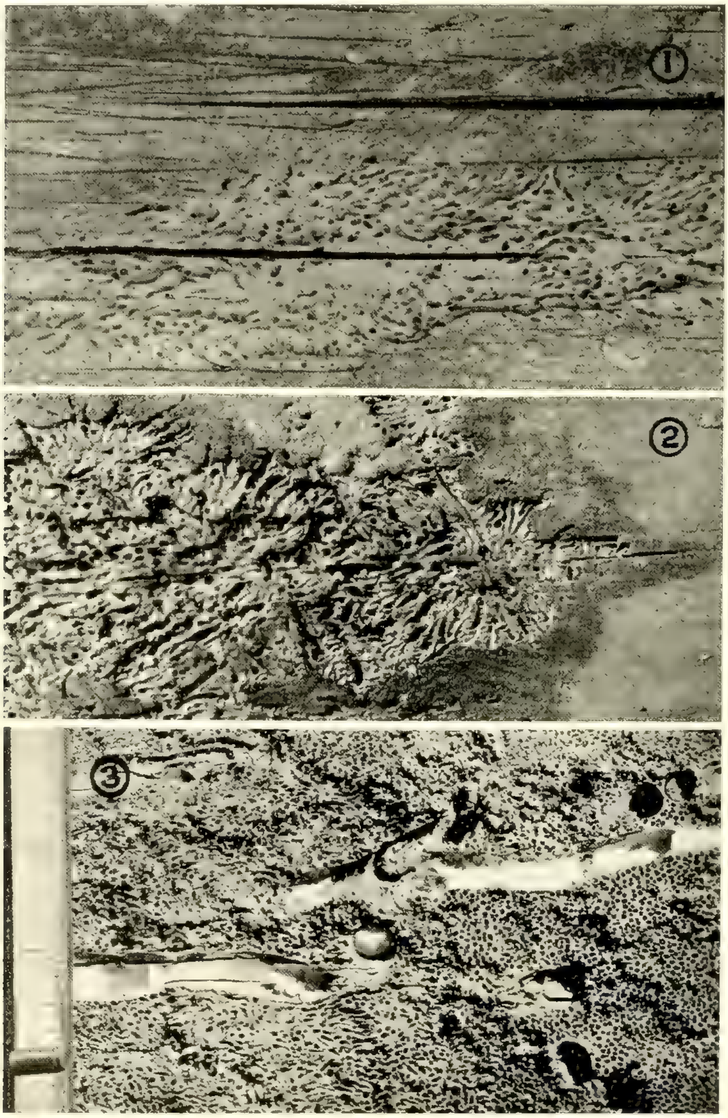


Fig. 133. (1) Untreated Oregon fir fender pile exposed one month, July, 1920, in Municipal Quay, Oakland Estuary. Initial attack of *Limnoria*.

(2) Untreated Oregon fir pile in Southern Pacific Oakland Mole. Deeper penetration by *Limnoria*.

(3) Untreated Oregon fir fender pile, driven in Oakland Municipal Quay in 1913, removed in 1920. *Limnoria* attack uncovering *Bankia* tubes.

Limnoria shows very definite reactions to any substance into which it may force its claws and so attach itself. This thigmotropic reaction shows itself particularly when the organisms are placed in a clean Petri dish. If there are no other objects

to which they may become attached they cling to one another. In this way a ball of a varying number of organisms is formed. There may be only two or three, or a dozen or more, individuals together in such a ball. It seems probable that this behavior is an expression of a reaction which leads the organisms to attach to all sorts of substances. Those which happen to attach to wood are able to bore into it, and become established there, and so survive.

The distribution of *Limnoria* in driftwood offers better chances of success than obtains in the distribution of detached organisms. Pieces of infected driftwood are frequently found, carried by the wind and tidal currents, between the piles of a wharf. Here they may become caught and subjected to severe erosion by the pounding of the waves. The superficial layers of wood which are more friable are thus worn away, and a large number of *Limnoria* liberated. It is here that the peculiar spiral and irregular course of swimming affords added possibilities of the organisms' becoming attached to a nearby pile or other structure.

It may be assumed, then, that distribution from wharf to wharf, and from locality to locality within a harbor, is accomplished in considerable measure through the agency of infected driftwood. The swimming abilities of *Limnoria*, and tidal currents, may account directly, however, for distribution over shorter distances, as among the piles of an infected wharf. A few piles of a wharf having become infected, they may serve as a source for the gradual infection of the entire submerged structure.

The Mechanism of Boring

The mechanical process by which *Limnoria* constructs its burrow has been observed in the case of individuals making an attack on a piece of Douglas fir. We were able in one case to watch an animal under the binocular without disturbing it for several days.

The body is firmly held in position by the peculiar arrangement of the legs and claw-like feet. The claws of the first three pairs of legs are directed backwards, while those of the four remaining legs are directed forwards. This arrangement permits of a very firm and tenacious attachment to a piece of wood. The legs of the fourth pair are directed more laterally than the others, giving support in this direction. Once they have become attached to the surface of a piece of wood it is found to be very difficult to wash the animals off with a stream of water, even though the force of the current be much greater than that which would normally be produced by the wash of the waves. The mechanism of attachment is of greatest service to the animal during the early stages of excavating the burrow, when it is on the exposed surface of the wood and entirely unprotected.

In the boring process itself there is a very vigorous action of the mouth parts, especially the mandibles and maxillipeds, combined with a slow turning motion of the head. Details of the action of the mouth parts are difficult to observe, as a sufficiently concentrated light to enable them to be seen disturbs the organism and it ceases its activity. We have been able to see, however, that in boring the head is pushed forward against the wood, the mandibles are brought into action, and then a quicker retractile motion is given the head. The posterior part of the body is moved very little and the turning motion of the head confines the boring to a limited area which becomes the burrow.

By carefully examining the edges of a burrow in process of construction one can see small but very definite serrations made by the pointed tips of the paired mandibles. Douglas fir shows these serrations particularly well, since the surface wood after soaking is generally reddish and contrasts well with the yellow wood exposed in the

burrow. Within the burrow itself the cuts produced by the mandibles are very difficult to see. It is these successive cuts, the outlines of which appear as the above described serrations, which result in the formation of the burrow.

Hoek (1893) has suggested that the antennae and antennules, because of their haired scales, might be used in boring. We have not observed any behavior to support this view. These appendages are laid back over the head of the animal and do not appear to take any direct part in the excavation of the burrow.

A peculiarity of the boring habit is the steadiness and continuity with which the work is carried on. Disturbance of the organism may cause it to suspend boring momentarily, but it quickly resumes its activity and continues steadily at work. At intervals the boring is interrupted and comb-like processes on the first pair of legs are used to clean the mouth parts.

Frequent observations were made on individuals in the early stages of making the burrow, and whenever observed they were found to be at work. One organism which had started its burrow on Saturday, April 26, was still boring at noon the following Monday, by which time the burrow was two-thirds the length of the body of the animal. When the light was turned on suddenly at night the animal was found to be boring steadily as during the day.

When disturbed the animal may react in one of several ways. An initial disturbance will cause it to crawl into the burrow as far as it can go. Continued mechanical stimulation will cause it to back out. It may then swim or crawl away, or if a more severe stimulus be given it will roll itself up into a ball as do many of the isopods, particularly the pill-bugs. It remains rolled up for only a few seconds. Animals which have become located in deeper burrows are slower to leave than those in new or incomplete burrows.

As the boring progresses, a considerable collection of oblong creamy white fecal pellets collect near the entrance of the burrow. They are discharged by the anus and forced away by the currents produced by the beating pleopods. They have a fibrous structure and are composed of the residue after passage of the wood through the digestive tract. These fecal pellets are very quickly attacked by bacteria, turning black and disintegrating within a few hours after their discharge. In this respect they differ from those discharged by *Teredo*.

So far as we have observed, no wood accumulates near the region of the head. All of the particles apparently pass through the digestive tract and are discharged through the anus, as in the case of the molluscan borers.

The passage of the wood through the digestive tract is rapid. The casts are quite regular in size and approximate one-tenth the length of the entire digestive tract. The average frequency of discharge is one in eight minutes. It is estimated, accordingly, that a given particle remains in the digestive tract about eighty minutes, and that there are eighteen complete passages in twenty-four hours. These observations are based on animals constructing new burrows, and therefore presumably working at a maximum rapidity.

The burrow gradually approximates the contour and size of the individual constructing it. It is at first a simple graded excavation, deeper at the forward end. By the end of twenty-four hours, according to our observations, the burrow is considerably deepened and the head entirely covered when the animal is in the burrow as far as it can go. From the rate of progress here and in other cases, we have noted that the time necessary to construct a burrow of such a size as to contain the animal is from four to six days. During this period the exposed position of the organism greatly increases the possibilities of its being washed away, or crushed. The arrangement of

the claw-like feet for attachment is particularly serviceable at this time. It is to be noted also that those organisms which bore more rapidly are more likely to survive this comparatively critical period of their life.

There is apparently a limit to the distance *Limnoria* will penetrate into the wood. The deepest burrows are generally within one-half inch of the surface. Burrows extending three-quarters of an inch from the surface are not often found. This limitation arises most probably from the difficulty of obtaining a sufficient supply of water with normal oxygen content in deeper burrows. Not only is the circulation of the water hindered by the tortuous path it follows in coming into the deeper lying burrows, but it is also partially deoxygenated by those organisms living in the more superficial burrows. In this connection, one finds on observing the lateral walls of the deeper burrows that numerous small holes have been made through them, connecting adjacent burrows. These holes are not sufficient in size to allow the body of the organism to pass through. They serve as an entrance for the currents of water produced by the action of the pleopods. The currents may be followed by placing some silt or small pieces of debris near these entrance points. The currents draw the material in around the sides of the animal, over the pleopods, and out through the entrance to the burrow.

As a result of these communicating passages the water circulates more freely and the organism can burrow more deeply into the wood. As the superficial exposed layers of wood are washed away more rapidly than the wood around the deep burrows, not only are those burrows which were formerly the deepest given an increased supply of sea water, but the majority of their inhabitants are left in place to continue the attack. Those more exteriorly situated are more likely to be washed away along with the wood they are inhabiting.

Since those organisms which bore more rapidly become located in the deeper burrows, differences in rate of boring may accordingly be operative as a survival factor here, as well as in the initial stages of making the burrow.

Digestion of Wood

As remarked above, all of the wood particles removed by *Limnoria* pass through its digestive tract. This raises the question of the probable utilization and digestion of this wood for the maintenance of the organism.

Wood appears to be the only substance which has ever been found in the digestive tract of this organism. In the examination of a considerable number of animals we have not been able to detect any other substance, and so far as we know, no other author has recorded finding anything except wood in the digestive tract of *Limnoria*.

It has been shown by several authors that the digestive tract of *Teredo* contains numerous diatoms and other plankton. On account of the very low protein content of wood, it has been suggested that *Teredo* obtains protein material by the digestion of these organisms.

Limnoria possesses no mechanism for filtering out plankton from sea water, such as that of the lamellibranchs. It must rely entirely, so far as we know, on what is taken into the mouth by the action of the mandibles and associated mouth parts. If *Limnoria* obtains its entire protein material from wood, it would be necessary for it to ingest a very large amount of that substance. As pointed out above in discussing the boring habit, much wood actually is ingested, and its passage through the digestive tract is rapid. Such rapid handling of the wood appears to be the only means by which sufficient protein can be obtained.

The carbohydrate requirements are probably supplied from the cellulose, ligno-

cellulose, and hemi-cellulose constituents of wood. An indication of digestion of the cellulose content of wood was obtained in the following way: The fecal pellets from a test block infected with *Limnoria* were allowed to collect in a jar of sea water. A portion of the same test block was removed by a fine-tooth file to serve as a standard. The iodine-zinc chloride reaction was used to compare the cellulose content of the two, by micro-chemical methods. The blue color resulting in the cellulose constituent of the wood is due to the formation of amyloid, and its reaction with the iodine. In the case of a yellowish wood such as Douglas fir the resulting color is, of course, quite green. In all cases the wood was examined microscopically, and only fibers or pieces of wood approximately equal in size were compared. It was found that the wood fibers always gave a considerably darker color reaction than those fibers contained in the fecal pellets. Some of the fecal pellets were ground up with glass in a small mortar, in order to remove any possible coating of mucus which might prevent the action of the reagent. A slightly darker color was obtained than with the normal fecal pellets, but a very considerable color difference between the wood fibers and fecal pellets could still be noted.

In order to determine whether or not *Limnoria* is able to utilize pure cellulose, about 25 organisms were placed in a jar of sea water containing two small sheets of a high grade of filter paper. Another similar jar was maintained as a control. The capacity of the jars was three liters. Both jars were cooled from the outside by running sea water. The organisms in the jar with filter paper lived two months and twelve days, only five surviving this long, however; they were still alive at the time the experiment was discontinued. The organisms in the control jar without filter paper were all dead at the end of the seventh week. There were thirty organisms in this jar.

In a number of places the filter paper was found to be gouged out over an area about equal in diameter to that of the body of *Limnoria*. The fecal pellets also showed clearly the fact that the filter paper had been ingested. It therefore appears probable that *Limnoria* is able to digest cellulose and utilize it for its maintenance. This experiment is regarded as preliminary in nature, however, on account of the limited number of organisms involved.

The Distribution of Limnoria in San Francisco Bay

The distribution of *Limnoria* in San Francisco Bay is shown in the frontispiece. In general, it may be said that the organisms occur in all portions of San Francisco Bay proper where wood is available for their attack. Damage occasioned by them is severe along the San Francisco and Oakland waterfronts, at Sausalito and Tiburon, and at the Dumbarton Bridge at the southern end of the bay. They are somewhat less active at Richmond, and become progressively less active above this point. At Point San Pablo and Point San Pedro damage to untreated piling by *Limnoria* proceeds very slowly, and beyond these points, in San Pablo Bay, it is practically negligible. On the west shore of San Pablo Bay occasional evidences of work and living organisms have been found as far as China Camp, a fishermen's colony about three miles beyond Point San Pedro. On the east shore they have not been found beyond Point San Pablo.

There has been some question whether the uppermost limit of the distribution of *Limnoria* is determined by the factor of lowered salinity, or merely by the absence of wharves and landings along the shores of San Pablo Bay for some miles above its entrance. The progressive decrease in the activity of this organism in the upper

portion of San Francisco Bay proper, however, indicates that the lower salinities prevailing in San Pablo Bay (see figs. 93 and 94) afford the deterring factor.

Some experimental evidence on this point will now be considered.

Effects of Low Salinity on Limnoria

There are two aspects of the effects of low salinity; one is the *lethal* or *death-producing salinity*, the other is the salinity at which the normal *activity* of the organisms is definitely retarded.

In order to determine the lethal salinity a series of glass jars of three litres' capacity were filled with sea water which had been diluted in varying amounts. The actual salinities were determined by titration at the conclusion of the experiment. As it is difficult to observe *Limnoria* directly without disturbing them, it was found more feasible to judge their condition by the amount of wood discharged during a given period.

In studying the lethal salinity the discharged wood was allowed to settle in Petri dishes placed in the bottoms of the jars. It was removed daily and an estimate made of the amount of wood present in each jar. The pieces of wood in each jar were all taken from the same test-board and contained approximately equal numbers of organisms. The results are given in the accompanying table (table 45). It will be seen that no wood whatever was discharged in jars No. 2 to No. 5, nor in No. 6, in a salinity of 6.5 parts per 1000. At this and lower salinities all of the organisms died within 24 hours. In jar No. 7, in a salinity of 10.7 parts per 1000, the discharge of wood was extremely small. The organisms in this jar were very sluggish and were not able to swim after two weeks. In salinities of 12, 14, 16 parts per 1000 there was a gradual retardation of activity, but during the two weeks of the experiment the organisms in these salinities survived and continued to bore. It therefore appears from these experiments that a salinity as low as 6.5 parts per 1000 is lethal within 24 hours, that a salinity of 10 parts per 1000 probably is ultimately lethal and that in salinities of 12, 14, 16 parts per 1000 there is a very decided retardation in activity.

TABLE No. 45

SALINITIES LETHAL TO LIMNORIA

The numbers refer to the wood discharged, the amount discharged in a salinity of 10.7 parts per 1000 being taken as 1; they represent approximate estimations only.

Jar Number	Salinity	Days 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
2	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	4.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	5.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	10.7	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	12.2	x	x	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	14.2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1
10	16.7	x	x	2	1	1	1	1	1	1	1	1	1	1	1	1	1
12	20.1	x	x	3	2	2	2	2	2	2	2	2	2	2	2	2	2
13	29.5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

In order to determine the actual retardation in activity of *Limnoria* by low salinity, we carried out a similar experiment to the above, but allowed the discharged

wood to collect over a period of 10 days and estimated it by means of sedimentation tubes. The results are shown graphically in figure 134. The amount of wood discharged at a salinity of 30 parts per 1000 was regarded as representing 100% activity, and the activity for the different salinities estimated accordingly. It will be noted that the activity at a salinity of 16 is 45% and at 10 is about 10% of the normal. That the organisms can survive salinities as low as 10 parts per 1000 for a period of two weeks has been shown by the experiments on the lethal salinity. But it seems very doubtful that an organism which is exhibiting only 45% of the normal in a fundamental activity will continue to live and reproduce in that environment.

This view is further supported by the distribution of *Limnoria*. The committee report of the Danish Engineering Association (1921) shows the limiting salinity for this organism in Scandinavian harbors to be 16 parts per 1000. They point out that

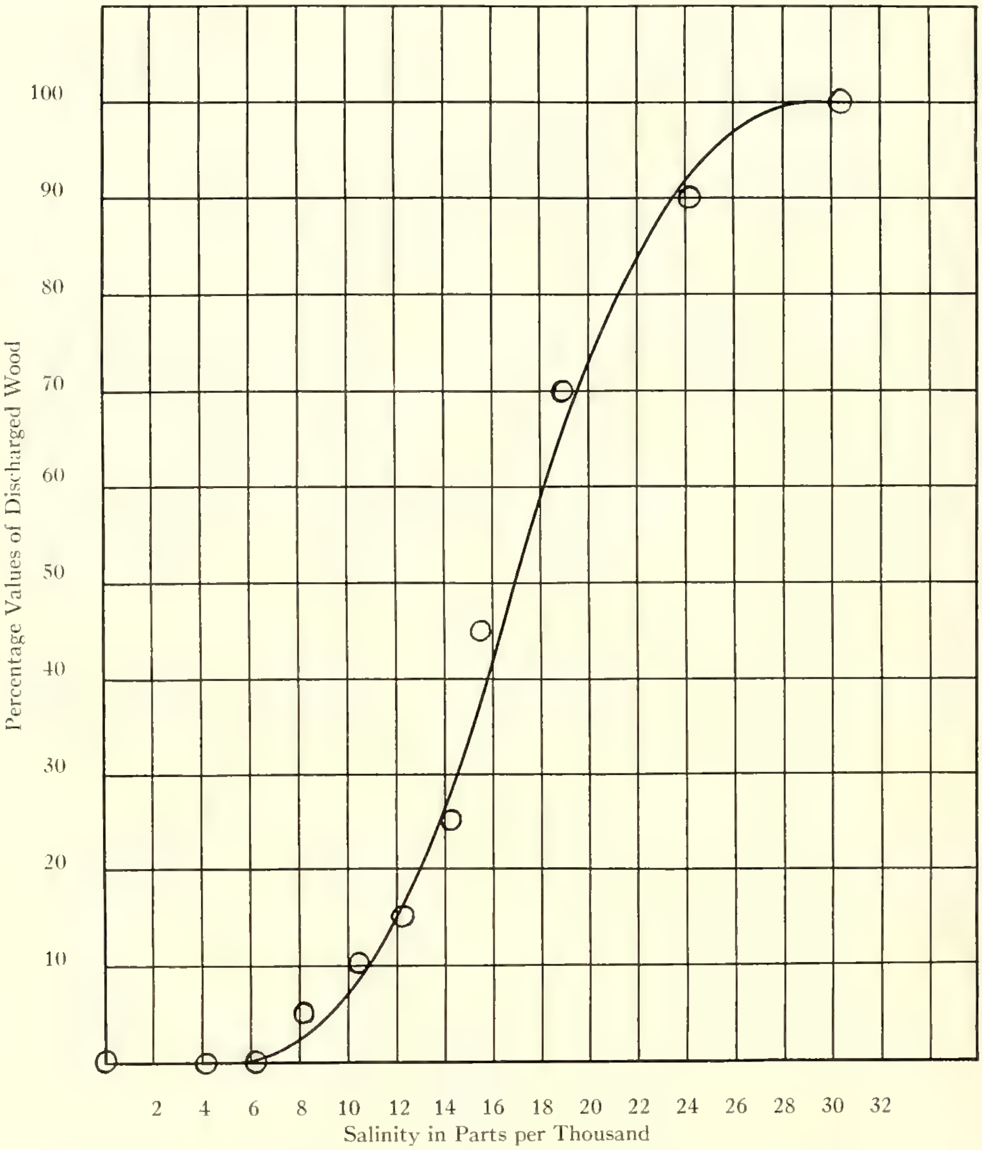


Fig. 134. Graph of the activity of *Limnoria lignorum* in water of various salinities.

the minimum salinity over a limited space of time determines the distribution of *Limnoria*. This is of course the case only when the average does not remain below 6.5, which we have found to be lethal in 24 hours.

Referring again to the distribution in San Francisco Bay, it will be observed from a study of the salinity graphs, figures 93 and 94, that at Black Point, a locality a few miles above the uppermost limit of the occurrence of *Limnoria* in San Pablo Bay, the average salinity approximates 11 parts per 1000, with occasional drops to 5 parts per 1000 or less. These figures should be weighted somewhat for the fact that Black Point is at the mouth of Petaluma Creek, and hence is perhaps not representative of the conditions in general along the west shore of San Pablo Bay.

Sumner, *et al.* (1914) reports average salinities in the lower portion of San Pablo Bay to be between 24 and 25 parts per 1000. His figures are based, however, on mid-channel samples, in years of less than normal rainfall. It is probable that the inshore waters of San Pablo Bay during years of normal rainfall and river discharge are for a considerable period below 16 parts per 1000, and, especially in the neighborhood of the mouths of small streams, they must frequently drop below the rapidly lethal salinity of 6.5 parts per 1000. It seems unlikely, therefore, that *Limnoria* will establish itself as an organism of economic importance in San Pablo Bay.

Breeding Habits of Limnoria in San Francisco Bay

Limnoria is dioecious, but the sexes do not show very decided secondary sexual characters. The most noticeable external difference between the male and female is in size, the female being the larger of the two.

When the eggs are extruded from the body through the oviducts they pass into the brood cavity, the lamellae of which become cemented together. The eggs undergo development in this cavity. They are bathed by a fluid which is probably secreted by the brood lamellae. When the extruded eggs fill up this chamber, the enlarged brood pouch renders the detection of gravid females easy. Ventral views of *Limnoria* with eggs in the brood pouch are shown in figs. 124 and 125. The number of eggs carried by a gravid female varies from 1 to 17; 17 is exceptional; 15 is fairly frequent. The average for twenty-one gravid females examined by us was 9.5. Coker (1923) in his work on the breeding habits of *Limnoria* at Beaufort, N. C., found the average in May to be between 4.2 and 6.6. Twelve was the maximum number observed at Beaufort.

In San Francisco Bay it has been found that gravid females occur during the entire year. There appears to be no season in which breeding entirely ceases, even though winter temperatures in the bay may fall as low as 8° C. Seasonal variation in the number of larvae in the brood pouch has not been studied by us.

At Beaufort it has been found that there is a definite breeding season and that it is correlated with the temperature. The data of Coker indicate that 14° C. is a critical temperature above which breeding occurs, and below which it ceases. The seasonal variation in temperature produces therefore an annual breeding season at that locality. It is to be noted, however, that the range in temperature at Beaufort is more than twice that in San Francisco Bay. According to Coker the range is 20.3° C. at Beaufort. In San Francisco Bay the range of temperature varies considerably with the locality; the greatest range is at Carquinez Strait, where it is 12.65° C; while the minimum range is at Golden Gate where it is 4.92° C. The conditions at both these localities are extreme and the annual range in the greater part of the bay is approximately 8.5° C.

Although the temperature in San Francisco Bay is much of the time below 14° C.,

this temperature does not act as a critical factor in the control of breeding, as it does at Beaufort. It appears therefore that the temperature of 14° is critical only when associated with a great annual variation in temperature, and the relatively small annual variation in temperature in San Francisco Bay may account for the lack of a definite breeding season of *Limnoria* in this region.

It is to be noted that *Limnoria* has been found as far north as Kodiak Island on the Pacific Coast and well within the arctic circle on the Scandinavian Coast. The temperature at these localities must always be less than 14° C.

Commensals and Parasites of Limnoria

The organisms which are attached to the body of *Limnoria* are related to it either as commensals or as parasites. The former consist of sessile Protozoa and the latter of a species of nematode and an unidentified organism, possibly a trematode.

The sessile Protozoa attached to the exterior of *Limnoria* are often very numerous. The telson, the ventral portions of the epimera, the basal joints of the legs, the mouth parts, the pleopods, the bases of the antennae, and the lamellae of the brood pouch serve as points of attachment for great numbers of these organisms. They apparently do not penetrate below the epidermis into the body of their host, but are merely attached to it by a sticky secretion at their bases, and for this reason we have indicated them as commensals.

The most commonly found include the following: *Folliculina, Spirochona, Epistylis, Opercularia* and *Cothurnia*. *Folliculina* sp. is found most frequently on the telson, but they also occur on the posterior segments of the abdomen. These organisms are frequently so numerous as entirely to cover the telson. The dark green tubes in which *Folliculina* live are very characteristic. They have been found on about 80% of the individuals examined.

Of the other commensals, *Spirochona* and *Epistylis* are probably the most numerous. *Spirochona* is frequently attached to the pleopods and *Epistylis* to the head and the epimera. Suctorians have been mentioned by Hoek (1893) as occurring on *Limnoria* but we have not seen them.

The parasitic nematodes are found in two places on the body of *Limnoria*. They are found loosely attached under the fold of chitin between the first segment and the head. There is a considerable space here and it is practically always invaded by these organisms in great numbers. As their presence here does not seem to be detrimental to the host they may be included with the commensals; they occur, however, in the brood-cavity containing the eggs and the liquid which bathes the latter, and their presence here should be regarded as parasitic, since they must obtain their nourishment from the fluid of the brood-cavity.

The other organism injurious to *Limnoria* has not been identified. We have only found it when encysted; no active animals have been seen. The cyst is approximately round and occurs near the base of the inner ramus of the pleopods. It presents a granular appearance but no definite structures have been seen. It has been suggested by Hoek that it is a trematode.

To summarize, we may say that there are numerous protozoa living as commensals on the body of *Limnoria*. There is also a nematode occurring in the brood-cavity and attached under a fold of chitin back of the head. There is a parasitic organism, possibly a trematode, often found encysted near the bases of the pleopods.

Limnoria in the Pacific Islands

Limnoria lignorum occurs in considerable numbers in Pearl Harbor and, with *Limnoria andrewsi*, in Honolulu Harbor. A light and scattered attack by *L. lignorum* has occurred in test blocks from Nawiliwili Bay, Island of Kauai.

The specimens from Hawaii are smaller than is usual for this species in our colder waters, averaging somewhat under 2.5 mm. in length. The length usually given for *L. lignorum* is 3 mm. In San Francisco Bay the average length of adults of this species is 3.5 mm.

Limnoria andrewsi (fig. 135) may be distinguished from *L. lignorum*, as from the five other known species of *Limnoria*, by the relative shortness of the peduncle of the uropods; this in *L. andrewsi* is equal in length to or shorter than the outer ramus or exopodite of the uropods, while in all of the other species the peduncle exceeds the exopodite in length.

This species occurs in the test blocks from Samoa in approximately the same numbers as *Chelura insulae* (*vide infra*). The result of the combined action of the two is shown in figure 136, *1*. *Limnoria andrewsi* also occurs with *L. lignorum* in Honolulu Harbor, where it greatly outnumbers the latter species, and at Nawiliwili, where both occur in limited numbers.

It is remarkable that, while *Limnoria andrewsi* is the dominant species in the test blocks from Honolulu Harbor, in the blocks from Pearl Harbor, only a few miles distant, *L. lignorum* predominates to such an extent that if *L. andrewsi* occurs at all its presence has been overlooked. No crustacean borers have been found in the limited number of blocks received from the Philippine Islands.

Genus Sphaeroma

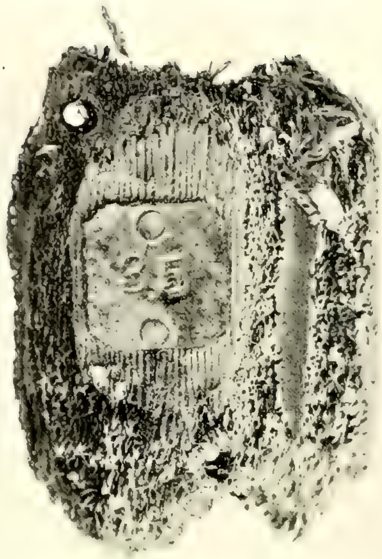
The crustacean borers of the genus *Sphaeroma* are much larger and stouter organisms than *Limnoria*, but with the same general structure. On account of their

1 2 3

Fig. 135. *Limnoria andrewsi* from Tutuila. 1, dorsal; 2, lateral and 3, ventral views of female carrying advanced embryos in brood pouch. × 17.

habit of rolling up into a ball when disturbed they are somewhat commonly known as "pill bug borers." In general they are not of much economic importance, but one or two species, particularly *Sphaeroma destructor* of the Florida Coast, are reported as occasioning considerable damage. Only one species occurs on the Pacific Coast of North America.

1



2

3

Fig. 136. (1) Portion of a $3\frac{1}{2}'' \times 3\frac{1}{2}'' \times 6''$ test block submerged eight months at Tutuila, showing damage by *Limnoria andrewsi* and *Chelura insulae*. The ends of a few *Teredo* burrows have been exposed. $\times \frac{3}{4}$.

(2) All that remained of a $2'' \times 3\frac{1}{2}'' \times 5''$ test block submerged eight months in Honolulu Harbor. The major damage was occasioned by *Limnoria andrewsi; Limnoria lignorum* and *Chelura insulae* were also present in the block. All *Teredo* were dead as a result of exposure of their burrows by the crustacean borers. $\times \frac{3}{4}$.

(3) Portion of block from Tutuila, showing *Chelura insulae* in place in burrows. One *Limnoria andrewsi* is seen in place near lower left corner. $\times 5$.

Sphaeroma pentodon Richardson

This is an organism averaging about 1 cm. in length, and about half as broad as long. Its color is dark olive to slightly reddish brown. It is often mottled or blotched with lighter dull yellowish areas on the middle of the back. The eyes are prominent and lateral in position. The surface of the body is minutely but densely granular. The posterior segment is evenly rounded in outline, and bears on its median surface two sub-parallel rows of four tubercles each. There is a prominent transverse elevation across its posterior border.

The outer mobile branch of the last pair of abdominal appendages bears five posteriorly directed denticulations, which serve the useful purpose of taking hold of the sides of the burrow and pushing or holding the head and gnawing mouth parts firmly against the bottom of the burrow.

The only organism with which this is likely to be confused is *Exosphaeroma oregonensis*, a related form which occurs commonly on the surface of piling in San Francisco Bay, and even in the burrows of *Sphaeroma*, but is not known to do any boring. This organism is similar in shape and appearance to *Sphaeroma pentodon*, but it lacks the regularly arranged excrescences on the terminal segment of the abdomen, and it does not have teeth on the outer ramus of the uropod.

Distribution and Habits

Sphaeroma pentodon (fig. 137) is generally distributed throughout San Francisco Bay, and may be anticipated at any locality, in salinities ranging from that of normal sea water down to that of waters that are only faintly brackish. It has been found

Fig. 137. Dorsal, lateral and ventral views of *Sphaeroma pentodon*. Richardson.

to occur at practically every point in the bay where search for it has been made, although damage by it at most localities is negligible. It occurs most numerously in the upper portions of San Pablo Bay, and its activities are extended some distance up from the mouths of the small streams that empty into the bay here. Thus it occurs well up in Napa Creek, and up Petaluma Creek at least as far as the Northwestern Pacific drawbridge just below the city of Petaluma. Its activities in test boards placed at this bridge are shown in figure 137. The organism also occurs throughout Suisun Bay, and as far upstream as Antioch, and probably beyond.

A frequent, and probably the normal, habitat of this species is clay and friable rock (Barrows, 1919). Its burrows occur in great numbers in a peat formation along

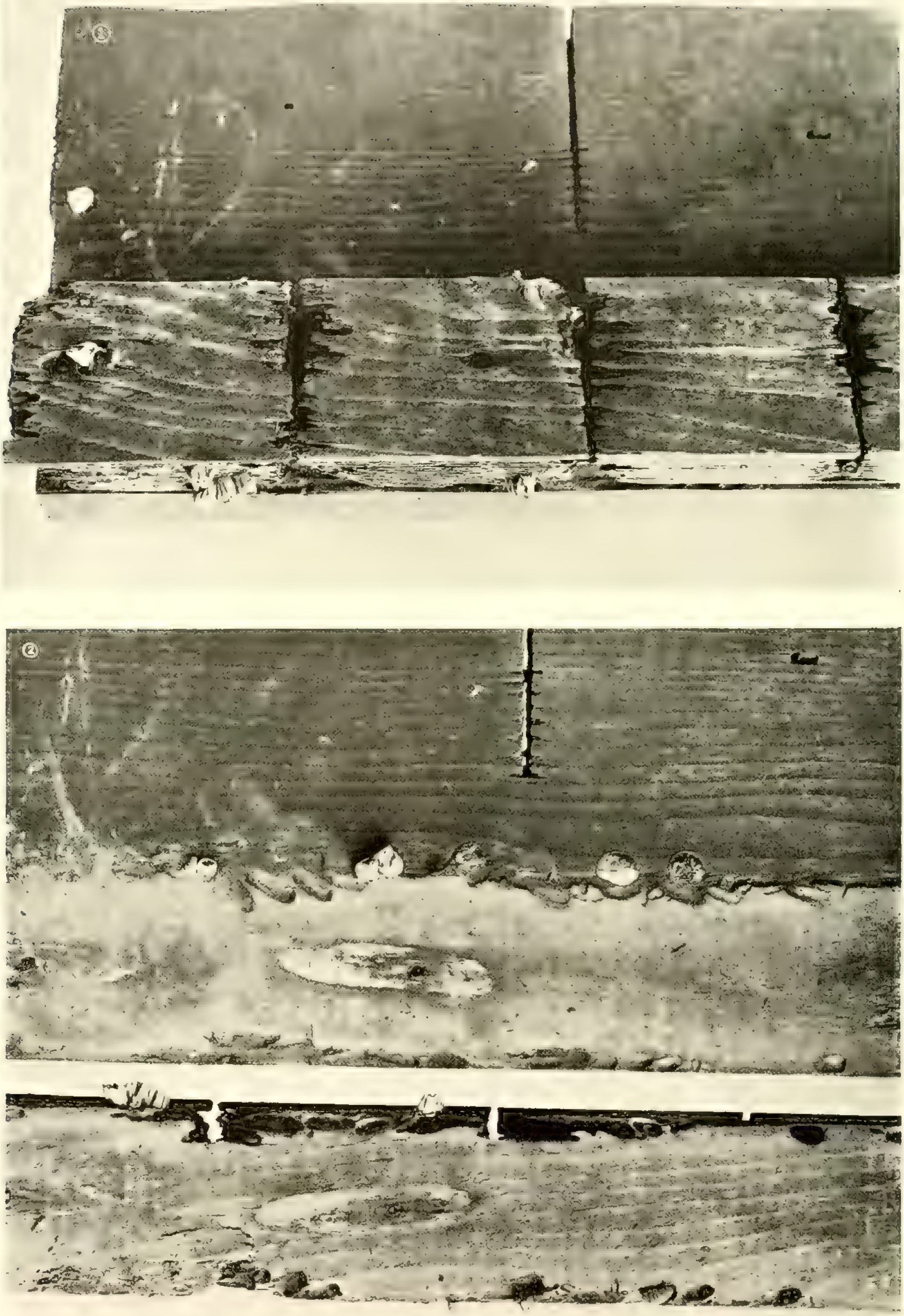


Fig. 138. Attack by *Sphaeroma pentodon* on test block in Petaluma Creek.
(1) Test block as removed from the water.
(2) Redwood strip taken off Douglas fir board, showing attack between the two.

the shore of Bay Farm Island, Alameda. Wood apparently plays the role of a secondary habitat, or the organism might be regarded as in a transitional stage of adaptation to a wood-boring life.

Sound Douglas fir piling is rarely attacked unless it be unusually soft and open grained. But the surface of piling that has been attacked and partly destroyed by *Teredo* is often secondarily attacked by *Sphaeroma*, which finds boring an easy matter in the already honeycombed wood. Most of the evidences of the work of *Sphaeroma* that we have seen have been in piling of this sort. The boring of this organism is apparently for the purpose of securing shelter only, and it accordingly imbeds itself in the first suitable substance with which it comes in contact, be that substance stiff clay, soft rock, or piling, the surface of which is already broken down by the activities of *Teredo*.

Fig. 139. Pile at China Camp, on the west shore of San Pablo Bay, attacked by *Sphaeroma pentodon* between tide levels.

Some instances have been observed, however, of damage to piling occasioned by this borer alone, in the absence of attack by *Teredo*. This has usually occurred in old piling that has been subjected to alternate wetting and drying between tides for many years, and its surface affected to such an extent that *Sphaeroma* easily finds lodgement in it. Such a case is that shown in figure 139. Much of the piling in which we have observed attack by *Sphaeroma* alone has been standing so long that the tops have been practically destroyed by dry rot, so that the damage occasioned by the borers is of little consequence.

The test board shown in figure 138 was exposed for three years at the Petaluma

bridge of the Northwestern Pacific Railroad. The slight attack by *Sphaeroma* during this period is practically all limited to the region of saw-cuts made in the board to facilitate the removal of sample blocks. In these crevices the borers found lodgement and worked a short distance in each direction. It is interesting to note that the redwood strip was attacked in preference to the Douglas fir board. *Teredo* and *Bankia* usually show a greater or less aversion to redwood. In this case, at least, *Sphaeroma* has not attacked the fir board at all, except to scrape a few depressions in its surface in the crevice between it and the redwood strip. The redwood seemed to be somewhat softer than the fir, which may explain the preferential attack.

The presence of a few barnacles indicates that the water at this locality is brackish.

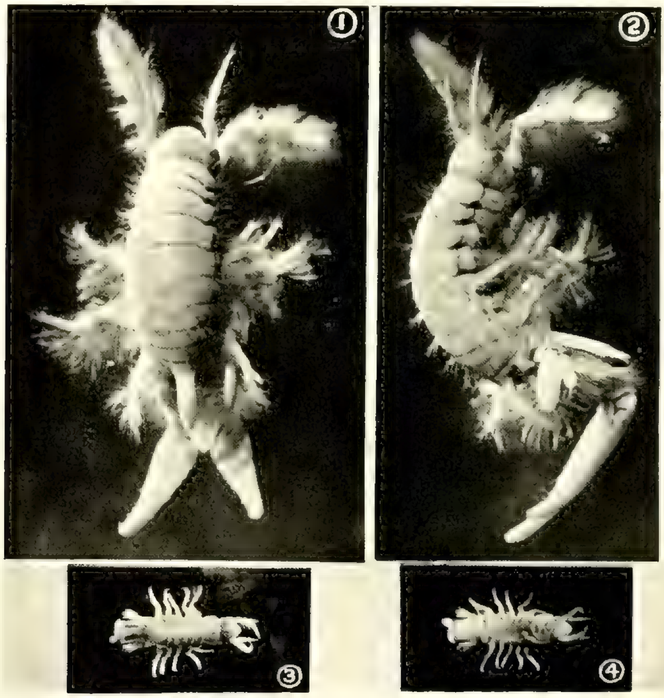


Fig. 140. (1) *Chelura terebrans*, male, from Charleston, S. C. Dorsal view. × 11.
(2) Same, lateral view. × 11.
(3 and 4) Dorsal and ventral views of female *Chelura*. × 5.

The excavations made by *Sphaeroma* in piling are very characteristic in appearance. They have large openings, up to nearly one-half inch in diameter, and often considerably longer than wide. They follow the grain of the wood, and do not exhibit the expansion inward characteristic of the burrows of molluscan borers. They are usually shallow, but some have been found three or four inches in depth.

Sphaeroma works mainly between high and low tides, although found at all levels on piling. Between tide levels it gives the piling a pitted appearance with its large, open, dark-colored burrows.

Nothing is known of the development or breeding habits of this species beyond the fact that the eggs are carried on the abdomen of the mother for a time, and that immature specimens are found in the spring, summer and fall in the burrows with the adults. It is not improbable that it breeds throughout the year as does *Limnoria* in San Francisco Bay.

Sphaeroma is often found in crevices or other sheltering nooks outside of its burrows, and is evidently something of a forager. Its stomach contents have been found to be made up of the minute vegetable and other growths which cover the surface of the piling. We have found fragments of wood in the intestine, but not in quantity sufficient to indicate that the organism feeds habitually on this substance, or depends upon it in any degree for its nourishment.

Genus Chelura

The members of this amphipod genus differ markedly from the isopod genera *Limnoria* and *Sphaeroma*. The body is more attenuated, somewhat laterally instead of dorso-ventrally compressed, and equipped with much more prominent appendages than the isopod borers possess.

Two species have been described, of which one occurs in Atlantic waters and the other in the Pacific Islands. Neither has as yet appeared on the Pacific Coast of North America. Both are apparently adapted primarily to tropical or sub-tropical waters, and are not of common occurrence in northern harbors, although *C. terebrans* has been reported along the coast of Europe from Norway to the Black Sea.

1

2

Fig. 141. *Chelura insulae* from Tutuila. (1) male. (2) female. Both × 17.

Chelura terebrans

This species is at present known from the Atlantic coasts of North America and Europe, from the Cape of Good Hope, and from New Zealand (see Calman, 1921). It will be briefly mentioned here for comparison with the only other known member of the genus, *C. insulae*, and in view of the omnipresent possibility of its introduction on the Pacific Coast.

The organism (fig. 140) is readily identified by certain rather marked characteristics, chief among which is the presence of a prominent, stout curved spine projecting from the posterior margin of the third abdominal segment on the dorsal side of the body. The body at the segmental joints, the antennae and the legs are clad with numerous long hairs. The terminal segments of the last pair of abdominal appendages in the male are highly modified as two long, stout, smooth club-shaped structures nearly half as long as the body.

Chelura works with *Limnoria* in marine structures, and has rarely, if ever, been reported as occurring in the absence of the latter organism; hence its presence may often be overlooked under such circumstances.

Chelura insulae Calman

This species (fig. 141) was described by Calman (1910) from Christmas Island in the Indian Ocean. It may readily be distinguished from *Chelura terebrans* by the longer antennae and antennules, the enormously developed anterior gnathopods, and absence of the prominent spine on the third abdominal segment which characterizes *C. terebrans*. In *C. insulae* the hind margin of the third abdominal segment carries three short tubercles. The brush of hairs on the third uropods of the male is a further peculiarity of this species.

Chelura insulae occurs in great numbers in the blocks from Samoa, following up *Limnoria* and enlarging the burrows of the latter for its own occupancy. The organism apparently bores for food as well as shelter, as the passages it makes (fig. 135, *3*) are considerably larger than would be required for the latter purpose alone. The appearance of wood that has been attacked by both *Chelura* and *Limnoria* (cf. fig. 135, *1*) is characteristically different from that which has been attacked by *Limnoria* alone.

Chelura insulae also occurs, though less numerously, in the blocks from Honolulu Harbor.

LITERATURE CITED

Andrews, A.

1875. *Limnoria terebrans* attacking telegraph cable. Quart. Jour. Micros. Sci., *15*, 332.

Barrows, A. L.

1917. An unusual extension of the shipworm in San Francisco Bay, California. Univ. Calif. Publ. Zool., *18*, 27-43.

1919. The occurrence of a rock-boring isopod along the shore of San Francisco Bay, California. Univ. Calif. Publ. Zool., *19*, 299-316, pls. 15-17.

Bartsch, P.

1916. A new *Teredo* from the west coast of America. Nautilus, *30*, 47-48.

1921. A new classification of the shipworms and descriptions of some new wood-boring mollusks. Proc. Biol. Soc. Washington, *34*, 25-32.

1922. A monograph of the American shipworms. Bull. U. S. National Museum, *122*, 51 pp., 37 pls., 1 fig. in text.

1923. Additions to our knowledge of shipworms. Proc. Biol. Soc. Washington, *36*, 95-102.

Bate, C. S., and Westwood, J. O.

1868. A history of the British sessile-eyed Crustacea. *2*. Isopoda (London, J. Van Voorst) lvi+536 pp., illus.

Blum, H. F.

1922. On the effect of low salinity on *Teredo navalis*. Univ. Calif. Publ. Zool., *22*, 349-368, 4 figs. in text.

Calman, W. T.

1910. On two new species of wood-boring Crustacea from Christmas Island. Annals and Mag. Nat. Hist., ser. 8, *5*, 181-186, pl. 5.

1919. Marine boring animals injurious to submerged structures. Brit. Museum, Nat. Hist., Econ. Ser., *10*, 35 pp., 21 figs. in text.

1921. Notes on marine wood-boring animals. 2. Crustacea. Proc. Zool. Soc. Lond., *1921*, 215-220.

Chilton, C.

1883. Additions to our knowledge of the New Zealand Crustacea. Trans. New Zealand Inst., *15*, 76.

Clapp, W. F.

1923. A new species of *Teredo* from Florida. Proc. Boston Soc. Nat. Hist., *37*, 31-38, pls. 3-4.

Coker, R. E.

1923. Breeding habits of *Limnoria* at Beaufort, N. C. Jour. Elisha Mitchell Sci. Soc., *39*, 95-100.

Coldstream, J.

1834. On the structure and habits of *Limnoria terebrans*. Edinburgh New Philos. Jour., *16*, 316-334, pl. 6.

Deshayes, G. P.

1848. Histoire naturelle des mollusques. I. Mollusques acéphalés (Paris, Imprimerie National), xx + 609 pp., atlas.

1863. Catalogue des mollusques de l'ile de la Réunion (Paris, Dentu), iv+144 pp., 14 pls.

Danish Engineering Association.

1921. Paeleorms og paelekrebs angreb ved Skandinaviens kyster. (Copenhagen) 47 pp., 21 figs. in text, 2 maps.

Dore, W. H., and Miller, R. C.

1923. The digestion of wood by *Teredo navalis*. Univ. Calif. Publ. Zool., *22*, 383-400, pl. 18.

Grunsky, C. E.

1921. Report of the sub-committee on the hydrography of San Francisco Bay, *in* Report on the San Francisco Bay Marine Piling Survey, *1*, 12-23, 2 figs. in text.

Harger, O.

1880. Report on the marine Isopoda of New England and adjacent waters. U. S. Fish Comm. Rept., *1878*, 297-462, 13 pls.

HARINGTON, C. R.

1921. A note on the physiology of the shipworm (*Teredo norvegica*). Biochem. Jour., *15*, 736-741, 1 fig. in text.

1922. Report of work done at the Marine Biological Station, Plymouth, July 1 to September 18, 1920. *In* Deterioration of structures in sea water; second (interim) report of the Committee of the Institution of Civil Engineers. Department of Scientific and Industrial Research (London, H. M. Stationery Office), pp. 35-43.

HATSCHEK, B.

1881. Ueber Entwicklungsgeschichte von Teredo. Arb. Zool. Inst. Wien, *3*, 44 pp., 3 pls.

HEWSTON, G.

1874. (Note on *Limnoria californica*) Proc. Calif. Acad. Sci., *5*, 24.

HOEK, P. P. C.

1893. Rapport der Commissie uit de Koninklijke Akademie van Wetenschappen, . . . betreffende de levenswijze en de werking van *Limnoria lignorum*. Verhandel. Koninkl. Akad. Wetenschappen, (tweede sectie) *1*, No. 6, pp. vi+103+(bijlagen) xcvi, 7 pls.

JEFFREYS, J. G.

1865. British Conchology (London, Van Voorst), *3*, 393 pp., 8 pls.

1869. *Idem.*, *5*, 259 pp., 102 pls.

KELLOGG, J. L.

1915. Ciliary mechanisms of lamellibranchs with descriptions of anatomy. Jour. Morph., *26*, 625-701, 72 figs. in text.

KINDLE, E. M.

1918. Notes on the habits and distribution of *Teredo navalis* on the Atlantic Coast of Canada. Dept of Naval Service, Biol. Contrib., *1916-17*, 91-101, 2 figs. in text.

KOFOID, C. A.

1921. The marine borers of the San Francisco Bay region. Report on the San Francisco Bay Marine Piling Survey, *1*, 23-61, 36 pls., 1 fig. in text.

KOFOID, C. A., AND MILLER, R. C.

1922. Specific status of the *Teredo* of San Francisco Bay. *Ibid.*, Biological Section, *2*, 81-82.

1923. An unusual occurrence of rock boring mollusks in concrete on the Pacific Coast. Science, *57*, 383-384.

LAZIER, E. L.

1924. Morphology of the digestive tract of *Teredo navalis*. Univ. Calif. Publ. Zool., *22*, 455-474, pls. 21-24.

LEACH, W. E.

1814. Crustaceology. Edinburgh Encyclopedia, *7*, 383-437, pl. 221.

1815. A tabular review of the external characters of four classes of animals which Linné arranged under Insecta. Trans. Linn. Soc. London, *11*, 306-400.

LEIDY, J.

1855. Contributions towards a knowledge of the marine invertebrate fauna, of the coasts of Rhode Island and New Jersey. Jour. Acad. Nat. Sci. Phila., ser. 2, *3*, 135-152, pls. 10-11.

MILLER, R. C.

1922. Variations in the shell of *Teredo navalis* in San Francisco Bay. Univ. Calif. Publ. Zool., *22*, 293-328, pls. 13-17, 6 figs. in text.

1923. Variations in the pallets of *Teredo navalis* in San Francisco Bay. *Ibid.*, *22*, 401-414, pls. 19-20.

1924a The boring mechanism of *Teredo*. *Ibid.*, *26*, 41-80, pls. 3-6, 6 figs. in text.

1924b Wood-boring mollusks from the Hawaiian, Samoan, and Philippine Islands. *Ibid.*, *26*, 145-158, pls. 8-11.

1924c Wood-boring Crustacea from Hawaii and Samoa. *Ibid.*, *26*, 159-164, pls. 12-13.

1926. Ecological relations of marine wood boring organisms in San Francisco Bay. Ecology, *7*, 247-254, 2 figs. in text.

MILLER, R. C., AND BOYNTON, L. C.

1926. Digestion of wood by the shipworm. Science, *63*, 524.

MILLER, R. C., RAMAGE, W. D., AND LAZIER, E. L.

1927. A study of physical and chemical conditions in San Francisco Bay, especially in relation to the tides. Univ. Calif. Publ. Zool., *31* (in press).

MOLL, F.

1914. Die Bohrmuschel (Genus *Teredo* Linné). Naturw. Zeitschr. Forst- und Landwirt., *12*, 505-564, 12 figs. in text. Bibliography.

1915. Holzzerstörenden Krebse. *Ibid.*, *13*, 178-207, 12 figs. in text. Bibliography.

NELSON, T. C.

1918. On the origin, nature and function of the crystalline style of lamellibranchs. Jour. Morph., *31*, 53-112, 17 figs. in text.

1922. The European pileworm, a dangerous marine borer in Barnegat Bay, New Jersey, N. J. Agric. Exp. Sta., Circ. *139*, 15 pp., 8 figs. in text.

NORMAN, A. M.

1869. Shetland final dredging report. Part 2. On the Crustacea, Tunicata, Polyzoa, Echinodermata, Actinozoa, Hydrozoa, and Porifera. Rept. Brit. Assoc. Advance. Sci., *1868*, 247-336.

PELSENEER, P.

1906. Mollusca. Lankester's Treatise on Zoology (London, Adam and Charles Black), part 5, 355 pp., 301 figs. in text.

PFEFFER, G.

1887. Die Krebse von Süd-Georgien. Pt. 1. Isopoden. Jahrb. Hamburg. wiss. Anstalt., *4*, 43-150, pls. 1-7.

POTTS, F. A.

1923. The structure and function of the liver of *Teredo*, the shipworm. Proc. Cambridge Philos. Soc. (Biol. Sci.), *1*, 1-17, pls. 1-2, 5 figs. in text.

QUATREFAGES, A. de

1849. Memoire sur le genre Taret (*Teredo* Linn.). Ann. Sci. Nat. Zool. (3), *11*, 19-73, pls. 1-2.

1849b. Memoire sur l'embryogenie des tarets. *Ibid.*, *11*, 203-238, 9 pls.

RATHKE, J.

1799. Jagttagelser henhorende til Indvolsormernes og Blöddyrenes Naturhistorie. Skrivter af Naturhistorie-Selskabet, *5*, 61-153, pls. 2-3.

RICHARDSON, H.

1905. A monograph of the isopods of North America. Bull. U. S. National Museum, *54*, liv + 727 pp., 740 figs. in text.

1909. Isopods collected in the Northwest Pacific by the U. S. Bureau of Fisheries steamer "Albatross" in 1906. Proc. U. S. National Museum, *37*, 75-129, 50 figs. in text.

SARS, G. O.

1897. An account of the Crustacea of Norway. *2*, Isopoda (Bergen, Museum), x + 270 pp., 104 pls.

SELLIUS, G.

1733. Historia naturalis teredinis seu xylophagi marini, tubulo-conchoidis speciatim Belgici (Trajecti ad Rhenum, Besseling), 353 pp., 2 pls.

SIGERFOOS, C. P.

1908. Natural history, organization, and late development of the Teredinidae, or shipworms. Bull. U. S. Bur. Fish., *27*, 191-231, pls. 7-21.

STEBBING, T. R. R.

1906. Marine crustaceans, XII, Isopoda, with description of a new genus; *in* Gardner, J. S., Fauna and Geography of the Maldive and Laccadive Archipelagoes (Cambridge, University Press), *2*, 699-721, pls. 49-53.

SUMNER, F. B., LOUDERBACK, G. D., SCHMITT, W. L., AND JOHNSON, G. E.

1914. A report on the physical conditions in San Francisco Bay, based on the operations of the United States Fisheries Steamer "Albatross" during the years 1912 and 1913. Univ. Calif. Publ. Zool., *14*, 1-198, pls. 1-13, 20 figs. in text.

TRYON, G. W.

1862. Monograph of the family Terededidae. Proc. Acad. Nat. Sci., Philadelphia, *14*, 453-482.

1863. Contributions towards a monography of the order of Pholadacea, with descriptions of new species, 2. Proc. Acad. Nat. Sci., Philadelphia, *15*, 143-145, pl. 1, figs. 2 and 3.

VAN OORDT, J. W. L., *et al.*

1864. Verslag over den paalworm. Uitgegeven door de Natuurkundige Afdeeling der Koninklijke Akademie van Wetenschappen (Amsterdam, Van der Post), pp. 1-37, tables 1-4.

1865. *Ibid., idem*, pp. 1-28, tables 1-4.

1869. *Ibid., idem*, pp. 1-28.

VROLIK, W., *et al.*

1860. *Ibid., idem*, pp. 1-158, pls. 1-3, tables 1-4.

1861. *Ibid., idem*, pp. 1- 20, tables 1-4.

1862. *Ibid., idem*, pp. 1- 16, tables 1-4.

1863. *Ibid., idem*, pp. 1- 18, tables 1-4.

VERRILL, A. E.

1873. Report upon the invertebrate animals of Vineyard Sound and the adjacent waters, with an account of the physical characters of the region. U. S. Fish. Comm. Rept., *1871*, 293-778, pls. 1-38.

WHITE, A.

1857. A popular history of British Crustacea (London, L. Reeve), xii + 358 pp., 20 pls.

YONGE, C. M.

1923. Studies on the comparative physiology of digestion. I. The mechanism of feeding, digestion and assimilation in the lamellibranch Mya. Brit. Jour. Exp. Biol., *1*, 15-63, 27 figs. in text.

1926a. Protandry in *Teredo norvegica*. Quart. Jour. Micros. Sci., *70*, 391-394, 2 figs. in text.

1926b. The digestive diverticula in the lamellibranchs. Trans. Roy. Soc. Edinburgh, *54*, pt. 3, 703-718, 2 pls.

APPENDIX A

San Francisco Bay Marine Piling Survey

PRELIMINARY QUESTIONNAIRE

(To be answered separately for each structure)

1. Name of company and officer reporting; address; date.

2. Name, if any, of dock or other structure; and ownership if not as under No. 1.

3. Location of structure. Date when first built.

4. Give plan of structure, showing especially its projection from shore.

5. Give profile of structure, showing water depth from shore line to outer end, for mean low and mean high tides.

6. Give for piling under structure: kind (when of wood, also species and whether treated or untreated), number (of each kind), age, condition.

7. Are marine borers attacking piling under this structure? If so, how serious is the attack? If not, are they active anywhere in the immediate vicinity?

8. Have you any data to show the life of untreated wooden piling in this structure or location? How, if any, does that life vary from shore line to outer end of structure?

9. What steps have been taken to protect this piling? Give dates, extent, and cost of repairs or replacements due to borer attack.

10. If piles are creosoted, have you any records of treatment available for study?

11. If there are coverings or other protections aside from creosote, describe them.

12. If piles are entirely of other construction than wood, what are they?

13. Can you give any further detailed information, such as salinity measurements, tidal and current movements, sewage or debris present in surrounding water, experiments which you have conducted, test specimens installed, etc.?

14. If desired, will you help in getting information such as under 13?

15. Can you give assistance in the examination of your structures for this survey?

16. Have any reports been made on this structure? If so, can a copy be furnished for use in the survey? Photographs?

17. Will any piling be removed under your jurisdiction within the next two or three months? Location and probable date of removal?

18. What is your estimate of the total damage, in terms of repairs or replacements, to date?

Please use a separate sheet for each structure, and address reply to

C. L. Hill,
U. S. Forest Service,
Ferry Building, San Francisco,
California.

APPENDIX B

Instructions for Cooperators in the Marine Borer Survey of San Francisco Bay

1. DETERMINING THE SALINITY OF WATER

Obtaining Water Samples

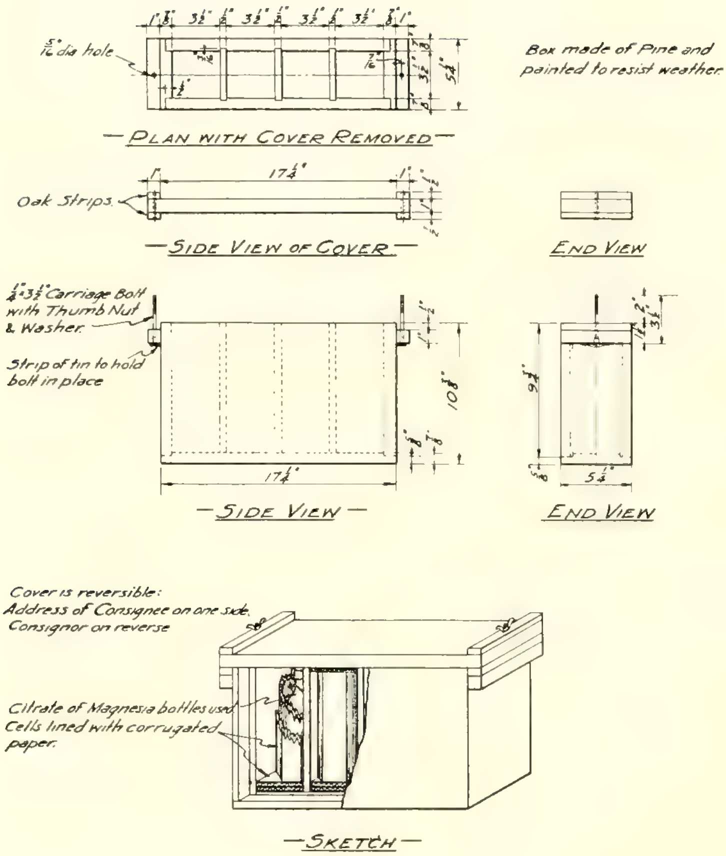
Sampling.—Samples of water should be taken always at the same determined stations. It is suggested that stations not already established at the date of receipt of these instructions be selected in consultation with the Forest Service engineers.* Samples should be taken at least once each week, from both the surface and near the bottom, and at both high and low tide. This will make not less than four samples for each station, at each weekly (or more frequent) period. Care should be taken to take the bottom samples each time at the same distance from the bottom (say 1 foot). This can best be accomplished by driving a nail in the structure from which the sampling is done, at a convenient point to the operator, and after determining the proper depth at the first sampling, to record the length of line used and indicate it by a knot in the line; then drop the sampling bottle always to the same depth from the nail for the bottom sample.

Apparatus.—Salinity samples may be taken either with a special lead-weighted copper salinity bottle such as that used by the S. P. Co., or with any suitable stout glass bottle of 12-ounce to 1-pint capacity, weighted so as to permit its sinking when empty. The common 12-ounce citrate of magnesia bottle is excellent. If a glass bottle is used it must be supplied with a solid stopper, through which a stout wire is driven and clinched on the under side, while the protruding end on the upper side is formed into a small ring. The lowering cord is then tied securely, say a foot from its end, to the ring in the stopper wire, and the end of the cord fastened tightly around the neck of the bottle so as to allow a few inches of slack between neck fastening and stopper ring. The friction of the stopper will permit the lowering of the closed bottle to the desired depth in the water, where it can be unstoppered by a quick jerk of the line. Should premature pulling of the stopper occur, it can be detected by the too early appearance of bubbles due to filling. If the citrate of magnesia pattern is not used, the bottle should in any case be as small-necked as will permit the proper wiring of the stopper, in order to avoid contamination of the sample by inwash of shallow water while raising the bottle.

Storage.—Each sample of water should be transferred from the sampling bottle to a thoroughly *cleaned* and drained storage bottle of approximately the same size, preferably glass stoppered, which should be tag-labeled with the number or name of station, date and hour of sampling, state of tide, whether sample is from top or bottom, and, for the latter, the height from bottom and approximate depth below surface at which taken. Analysis of the samples can then be made at convenience, except that analysis results should be sent in currently, without too great delay.

Shipping.—If the water samples must be transported by common carrier, to the laboratory or otherwise, a case constructed in accordance with the accompanying diagram will be found to combine a high degree of safety and convenience.

*Address by letter, C. L. Hill, Ferry Building, San Francisco, California; telephone Kearny 5869.



SHIPPING BOX FOR WATER SAMPLES
SAN FRANCISCO BAY SALINITY INVESTIGATION
Scale: 1 1/2":1'-0"   Date: Dec. 1920
Designed by F.H.Gilman, Asst. Engr. NW.P.R.R. Co

Fig. 142

Analysis.—The method selected as best adapted to our needs is the Mohr method of determination of chlorine by titration with silver nitrate, with a numerical modification designed to permit the reading of results in parts of chlorine per 1000 parts of water analyzed, from the burette reading of c.c. of silver nitrate solution required for reaction, with the least possible amount of computation.

Preparation of Solutions.—Prepare a standard solution of silver nitrate by dissolving 23.9545* grams of chemically pure crystals of silver nitrate, which has first been carefully dried, in distilled water to make exactly 1000 c. c. Also prepare a 10 per cent solution of chemically pure potassium chromate, which will be used as an indicator to show the end of reaction.

Testing of Standard Silver Nitrate Solution for Standard Strength.—This should be done at frequent intervals as follows: Dissolve 0.0824 grams of chemically pure *dried* sodium chloride in any convenient amount of distilled water. This amount of sodium chloride will require exactly 10 c.c. of standard solution of silver nitrate for complete reaction. Add to the sodium chloride solution a few drops of potassium chromate indicator, as above prepared. Then drop by drop, from a burette add the silver nitrate solution to be tested, stirring constantly until the appearance of the permanent red color of silver chromate indicates that the reaction is complete. If more or less than 10 c.c. of the silver nitrate solution is required to complete reaction, repeat the test and record the average ratio of standard to actual amount (e.g., if 9.5 c.c. are used, ratio = 10/9.5 = 1.0526), to be applied as a correction factor to all burette readings with that lot of solution.

It should be borne in mind that there is a large source of possible error in the judgment of the point at which the red indicator color becomes permanent. The titration should proceed slowly and with great caution as soon as red begins to appear.

To analyze Water Sample for Salinity.

1. Filter sample of water to be tested, if turbid.

2. Weigh out 5 grams of the filtered sample, on a balance sensitive to 1/10 milligram, and add to it 25 or 30 c.c. of distilled water.

3. Add 10 drops of the 10 per cent potassium chromate indicator.

4. From a burette graduated to 1/10 c.c. add standard solution of silver nitrate, a drop at a time, and stir constantly until the end of reaction is indicated by appearance of permanent red color. Then carefully take burette reading.

This analysis should be repeated at least three times on each sample and the average of results taken, unless the first two analyses agree.

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*On the basis of 1920 international atomic weights. This solution strength is based on the amount required for a decinormal solution (16.989 grams) multiplied by the factor 5/3.546, which is derived as follows: In the method for analysis of water, as set forth below, assume the use of a decinormal solution of silver nitrate; then each c.c. of the decinormal solution would represent 0.003546 grams of chlorine in the reaction. Now let a = the number of c.c. of decinormal solution required for complete reaction on b grams of water taken for test. Then

$$\frac{a \times 0.003546 \times 1000}{b} = \frac{a \times 3.546}{b} =$$

parts of chlorine in 1000 parts of water as analyzed. If, now, the strength of the silver nitrate solution be increased to 5/3.546 times that of a decinormal solution, the parts of chlorine per 1000 parts of water will be given by the ratio

$$\frac{a \times 5}{b}$$

or the number of c.c. of standard silver nitrate solution required for complete reaction multiplied by the ratio of 5 over the number of grams of water analyzed. If, then, 5 grams of water be taken for analysis, the parts of chlorine per 1000 of water will be given directly by the number of c.c. of silver nitrate solution required for complete reaction, without further computation, as used in the analysis method.

5. Assuming that the silver nitrate solution is of standard strength and that 5 grams of water are taken for analysis, then the number of c.c. of silver nitrate solution required for complete reaction will represent the parts of chlorine per 1000 of water analyzed, without further computation.

6. By reference to the international hydrographic tables* the parts of chlorine per 1000 (column 1, marked "Cl") can be read directly into total salinity (column 2, marked "S"). This "salinity" represents the oceanic portion of bay waters only and neglects the stream and seepage, or land water, contributions, since the marine borers are only adapted to the normal saline complex of sea water.† All salinity results for this survey should be represented in terms of this calculation of total salinity, in parts per 1000, in accordance with these tables.

Current Record and Disposition.—The results of each weekly or other periodic analyses should be tabulated in triplicate against the data obtained from the tag-label of each water sample. One copy may then be kept by the cooperator, while the remaining two are to be mailed to the U. S. Forest Service, Ferry Building, San Francisco, Calif., attention of C. L. Hill, by whom one set of all analyses will be sent to Professor C. A. Kofoid at the University of California for use in the biological studies.

II. TEST PIECES

For the purpose of recording the activity of borers, test pieces of untreated timber will be planted at points to be selected by the Committee or the engineer of the survey. Specifications for making these test pieces are given on the accompanying diagram. The pieces can be put down securely by pushing the end slightly into the mud and tacking the top to a convenient point on the structure by which the test station is located.

The use of such test pieces, as described below, is the best means so far devised to make possible continuous information respecting the inception, character, and rate of progress of a marine borer attack at a specified point, and therefore a judgment respecting the probable condition of and the degree of danger to adjacent structures. For this purpose one test piece should be installed each month, beginning preferably, in this climate, with the calendar year or some time during the rainy season, while the salinity is lowest in bay areas affected by land water discharge. Each month there should then be taken off from all the test pieces previously installed the bottom saw-cut section (or that one whose position has been next above the mud line), together with the attached redwood block. Except in the case of the first test piece put down, there is no need of keeping a given piece in position more than one year. There will then be obtained each month as many test sections as the number of months during which the test has been in progress, up to one year, and after that a continuing series of 12 sections, of which one was installed during each month of the preceding year. To give continuing information on the relative intensity of attack at different levels, the first piece put down should have the saw-cuts extend not over half through the width of the piece, so as to leave a substantial strip to support all the remaining

*"Hydrographische Tabellen" by Martin Knudsen; prepared under the authority and direction of the International Council for the Exploration of the Sea. Published by G. E. C. Gad, Copenhagen, 1901. The formula on which these tables are based is: $S = 1.8050\ Cl + 0.030$.

†Therefore determination of the salinity of brackish waters by the weight of solids left on evaporation is not valid for the purposes of the Marine Borer Survey.

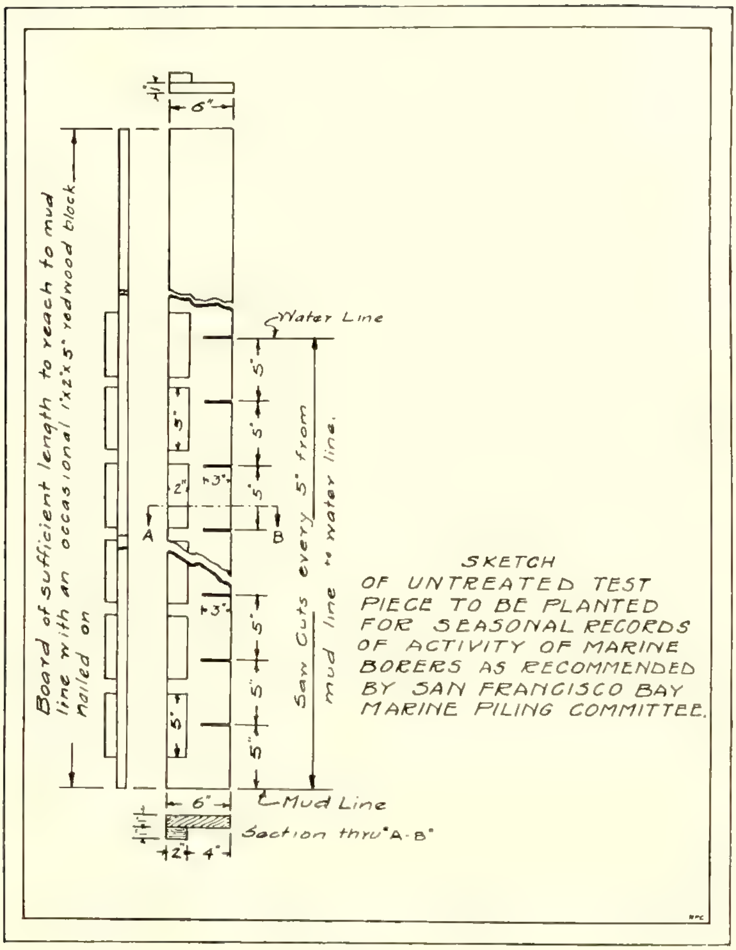

Fig. 143

saw-cuts at their original level as long as it is not destroyed by borers. The value of such a record, as much from the engineering and commercial standpoint as from the scientific, is many times more than its cost.

For purposes for which the above method is deemed too elaborate or costly, useful information can be secured by installing two test pieces at each station. The monthly sections are then taken from one piece and the other is left intact, an examination of the latter being made whenever sections are taken from the former.

Test stations should be located at the points of most rapid and severe attack. Such points can usually be anticipated as the points of most rapid current, or in the absence of current, of tidal flow, and in the deeper water.

Test sections, as removed, should be labeled with the name or other designation of the station, the test piece and saw-cut section numbers, and the dates of installation and removal. Those to be used for the purposes of the San Francisco Bay Marine Piling Survey should be wrapped securely and mailed to Professor C. A. Kofoid, East Hall, University of California, Berkeley, California.

III. SPECIMENS OF WOOD AND BORERS

Specimens showing the borers present, or illustrating the nature and progress of attack, are desired from as many localities as possible. Such specimens will be valuable for:

1. Piling or other wooden structures which will throw light on date of invasion or rate of destruction in any locality.

2. Invaded piling or structures giving similar information, especially in territory hitherto exempt from borers.

Specimens should be accompanied by complete data. The specimens may be of two kinds:

1. Wet specimens containing the living or undried animals. These should not exceed 12 inches in length, and should be selected to exhibit typical areas of heavy destruction of the different kinds of borers. They may be from either service piles and timbers or planted check timbers. Specimens should be sawed and split out with care and placed promptly in formalin (or formaldehyde) in a tub or pail. Formaldehyde can be obtained at any drug store and comes of a strength of approximately 40 per cent. A dilution to about 1 part formalin (as purchased) to 20 parts of water (salt or fresh) will pickle the animals in place in the wood in twenty-four hours. The sample may be left indefinitely in the formalin without harm. For shipment the sample may be wrapped while wet in a heavy covering of newspapers and shipped promptly, preferably in a tin or other tight box.

2. Dried sections not exceeding 18 inches in length, with invading borers dried in place, or their shells, whenever possible. Specimens should be protected for shipping by wrapping with burlap or a heavy covering of paper and suitably boxing them. Specimens of this kind have a great deal of value, if properly prepared and protected, and should not be neglected, especially when wet specimens containing the living animals are not available.

All specimens for the determination of the borers at work in each locality should be sent by parcel post or express, prepaid, to Professor C. A. Kofoid, East Hall, University of California, Berkeley, California.

IV. RECORDS OF PILING OR OTHER STRUCTURES ATTACKED BY MARINE BORERS IN SAN FRANCISCO BAY OR TRIBUTARIES

Authentic records giving the essential information in regard to past developments in borer infestation will be invaluable. Such records like the specimens, will be valuable for either:

1. Piling or other wooden structures which will throw light on the date of invasion or rate of destruction in any locality.

2. Invaded piling or other structures, giving similar information, in territory hitherto exempt from borers.

Bulky reports, or other documents, which it is not feasible to copy. If by any chance you have an extra copy which you can forward to the U. S. Forest Service, Ferry Building, San Francisco, California, attention of Mr. C. L. Hill, do so. If you have no such extras, please send to Mr. Hill a list of the reports which you have, with brief

description, giving for each title, material covered if not sufficiently given by the title, author, date, number of pages, and whether you could send it to the Forest Service as a loan, if desired, and for how long, or if not, it could be used for consultation at your office.

Reports made or which you could make specifically for this survey. Are there any important or interesting phases of the marine borer infestation which you could report on for the benefit of those who are working on the survey? Advise Mr. Hill about it. Such records or reports should cover, or at least not overlook all the points listed in the questionnaire recently issued, and which were, with slight modification, as follows. (Omitted here; see Appendix B.)

In addition to the above information (or if that has already been reported, a reference to such report), these reports should give all possible light respecting kind of borer and nature of working (especially by specimens, on which see above); location of working or of marginal and most severe zones of attack, respectively, with respect to mud line, low and high tide depth, etc.; as well as nature of exposure with respect to tide currents, fresh water seepage, sewage influx, debris breeding centers, or any other factors which you believe may have affected the life and attack of the borers in the material in question.

Whenever possible all reports prepared specially for this survey should be prepared in triplicate, so that one copy can be sent to the U. S. Forest Service, Ferry Building, San Francisco, attention of C. L. Hill, and another to Professor C. A. Kofoid, East Hall, University of California, Berkeley, California.

Miscellaneous observations and notes.—Notes on anything which interests you in respect to the marine borer situation will probably be of interest for the survey, and may be exactly the point missed by others. Dictate memoranda on all such points and send them in to the Forest Service. We can better afford to have some such material which is not used than to miss important information by neglecting such notes.

Photographs.—Good photographs are greatly desired. In no other way can many things be told so plainly. Many photographs will be taken in the course of the survey; but if we knew what you had it might save time and money; and you may have a better picture of some important feature than anybody else will ever take. If your collection is not too extensive, can you have copies, carefully labeled, made and sent to Mr. Hill at the Forest Service? If that is not feasible, will you write him about it, so that arrangements can be made to look over your collection and get copies of the items most essential for our purpose?

Issued October, 1920, for the San Francisco Bay Marine Piling Committee of the American Wood-Preservers' Association, by Sub-committee on Instructions:

E. M. Blake,
F. D. Mattos,
Professor C. A. Kofoid, University of California.
T. G. Townsend, Engineer of Survey,
C. L. Hill, in Charge, Office of Forest Products, U. S. Forest Service, San Francisco, *ex officio* as Executive Officer of the Committee.

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